Planetary Nebula

*{**Abstract** – In this segment of our "How far away is it" video book, we cover Planetary Nebula.*

We begin by introducing astrophotography and how it adds to what we can see through a telescope with our eyes. We use NGC 2818 to illustrate how this works. This continues into the modern use of Charge-Coupled Devices and how they work. We use the planetary nebula MyCn18 to illustrate the use of color filters to identify elements in the nebula.

We then show a clip illustrating the end-of-life explosion that creates objects like the Helix Planetary Nebula (NGC 7293), and show how it would fill the space between our Sun and our nearest star, Proxima Centauri.

Then, we use the Cat's Eye Nebula (NGC 6543) to illustrate expansion parallax. As a fundamental component for calculating expansion parallax, we also illustrate the Doppler Effect and how we measure it via spectral line red and blue shifts.

We continue with a tour of the most beautiful planetary nebula photographed by Hubble. These include: the Dumbbell Nebula, NGC 5189, Ring Nebula, Retina Nebula, Red Rectangle, Ant Nebula, Butterfly Nebula, , Kohoutek 4-55, Eskimo Nebula, NGC 6751, SuWt 2, Starfish, NGC 5315, NGC 5307, Little Ghost Nebula, NGC 2440, IC 4593, Red Spider, Boomerang, Twin Jet, Calabash, Gomez's Hamburger and others culminating with a dive into the Necklace Nebula.

We conclude by noting that this will be the most likely end for our Sun, but not for billions of years to come, and we update the Cosmic Distance Ladder with the new 'Expansion Parallax' rung developed in this segment.}

Introduction

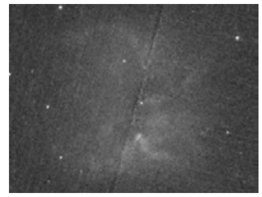
> ***[Music @00:00** Bizet, Georges: Entracte to Act III from "Carman"; Orchestre National de France / Seiji Ozawa, 1984; from the album "The most relaxing classical album in the world…ever!"]*

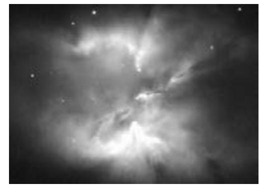
Planetary Nebulae represent some of the most beautiful objects in the Milky Way. In this segment, we'll talk about what they are and how far away they are. And I'll show you some of the spectacular pictures taken by the Hubble Space Telescope.

Astrophotography

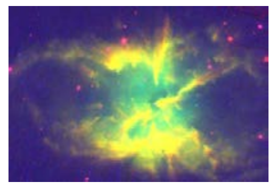
But first, I'd like to take a minute to go over how we create these photographs. When someone looks through a telescope, the light from the object falls on a person's eye. To take a photograph, all you have to do is replace the eye with a photographic plate.

Here we see Planetary Nebula NGC 2818. It's what someone would see if they were looking through the telescope. It's just a wisp. It's very nebulous. That's how it gets its name Nebula by the way. To the untrained eye, it might look like nothing at all. But if we increase the time exposure, and let more and more light from the object fall on the photographic plate, we get dramatically better results. We get a much sharper image. It's no longer a wisp. We begin to see there's something serious there with structure.





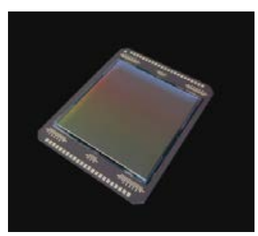
Then repeating the process with a filter using a small frequency band of light gives us the first pass on color. Repeating the process with different bands and combining the photo's produces the full astronomical photo effect. The frequencies bands chosen can represent different temperatures of gasses, or different colors might be used to represent different elements present in the nebula. In NGC 2818 we have: red represents nitrogen; green represents hydrogen; and blue represents oxygen.



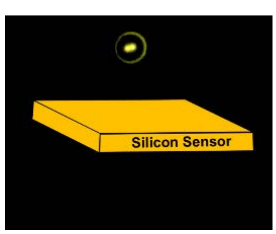
*[**Music @02:29** Puccini, Giacomo: La Boheme, Act I: Mimi's Aria - "Si, mi chiamano mimi" (Instrumental Version); Sofia Philharmonic Orchestra, 2015; from the album "100 Must-Have Opera Karaoke"]*

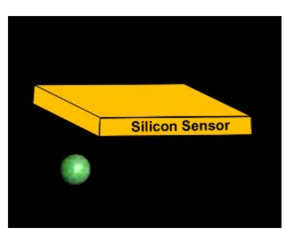
CCDs

Of course, today's telescopes no longer use photographic plates. Instead, a Charge Coupled Device (or CCD for short) is used. These enable direct connections between an object's incoming photons and its image on a computer. Here's how they work.



CCDs are based on a principle called the photo-electric effect. If a photon with sufficient energy hits an electron in the outer shell of an atom, the transfer of energy to the electron can be enough to free it from the atom altogether. [This is a foundational component of quantum mechanics first analyzed by Albert Einstein in 1905.]





CCDs use a thin wafer of silicon to produce electrons from photons because you can free a silicon electron with as little as 1.1 eV. That corresponds to a near infrared photon [λ = 1.13 μm]. And it doesn't start reflecting light instead of absorbing it until it reaches over 4.1 eV. That corresponds to blue-violet light [λ = 0.30 μm].

Photoelectric effect

$$E = hc/\lambda$$

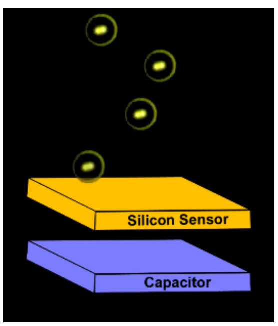
Where:

- E = energy
- λ = photon wavelength
- c = speed of light = 2.998×10^8 m/s
- h = Planck's constant = 4.136×10^{-15} eV-sec

If $\lambda > 1.13$ μm
Then $E < 1.1$ eV
And no free electron is produced

If $\lambda < 0.30$ μm
Then $E > 4.1$ eV
And the photon is reflected,
and no free electron is produced

A tiny positively charged capacitor is attached to the silicon wafer in order to collect the freed electrons. If we get one electron for each photon in the range, we'd have 100% quantum efficiency. The highest quality CCDs can achieve up to 90% quantum efficiency. It's interesting to note that the quantum efficiency of the human eye's rods and cones is only 1%.

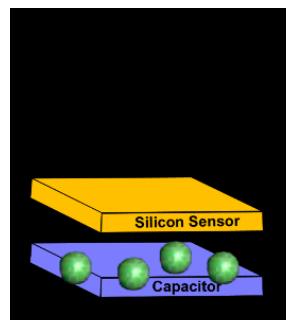


Quantum Efficiency

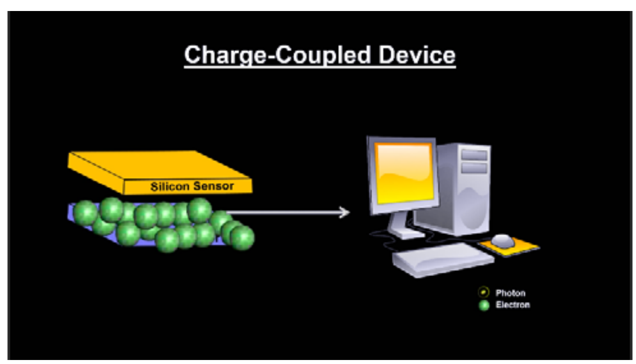
$$(N_e/N_p) \times 100\%$$

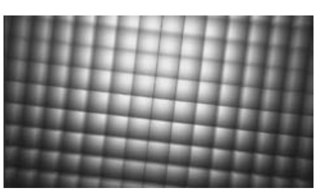
Where

N_e = number of electrons
N_p = number of photons



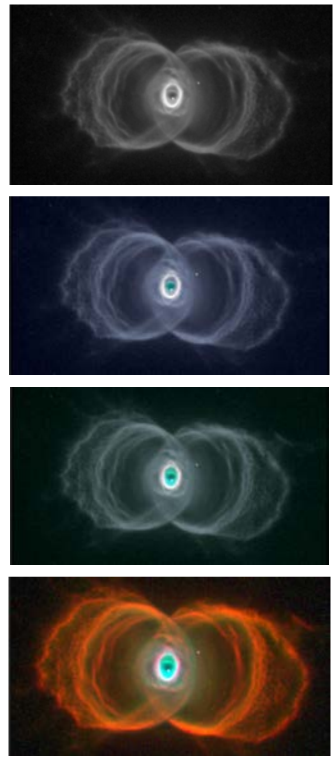
The phonons start producing electrons as soon as the shutter is opened. The capacitor collects the freed electrons until the shutter is closed. At that point, the voltage across the capacitor represents the number of electrons the capacitor collected. This information is sent to the computer.





All of this is miniaturized into an integrated circuit and represents one pixel. CCDs are made of thousands or even millions of these, configured as an array. The CCD on Hubble's Wide Field Camera 2 has two 2k by 4k arrays for an 8 megapixel CCD.

And as before for color, we simply repeat observation with filters. For example, here's Hubble's photograph of the planetary nebula MyCn18, 8000 ly away. This picture has been composed from three separate images taken with a blue filter to identify light from oxygen, a greed filter to identify light from hydrogen, and a red filter to identify light from nitrogen. The element distribution is of great interest because it helps us understand the ejection of stellar matter which accompanies the slow death of Sun-like stars.



*[**Music @05:14** Bach, Johann Sebastian: Air 'on the G string'; Academy of St. Martin in the Fields – Sir Neville Marriner, 1974; from the album "The most relaxing classical album in the world…ever!"]*

<u>Star End of Life Explosion</u>

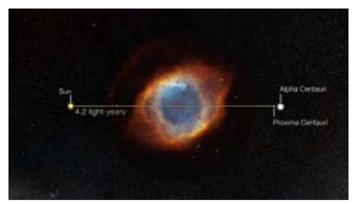
As you can see from these first two examples, Planetary Nebulae are not about planets. They're about stars. It got the name 'planetary' when early astronomers using small primitive telescopes first spotted these objects. They looked like disks similar to Jupiter and Neptune. Planetary Nebulae are actually stars like our Sun that are going through a typical end-of-life cycle.

They have ejected much of their mass into their surroundings and then collapsed in an explosion that ejects a massive amount of additional material at much higher velocities. The faster moving material crashes into the slower moving stuff to create spectacular formations.

Helix Nebula, NGC 7293 – 650 ly

This Helix Nebula is just one of them. Here we have the fluorescing tube or doughnut where we are looking right down the middle of it. A forest of thousands of comet-like filaments, embedded along the inner rim of the nebula, point back towards the central star, which is a small, super-hot white dwarf. That's what's left after the explosion. Each filament is around the size of our entire solar system!

Based on the nebula's distance of 650 light-years, triangulating its angular size corresponds to a huge ring with a diameter of nearly 3 light-years. It would fill most of the space between our Sun and our nearest star – Proxima Centauri.



Cat's Eye Nebula, NGC 6543 – 3,264 ly

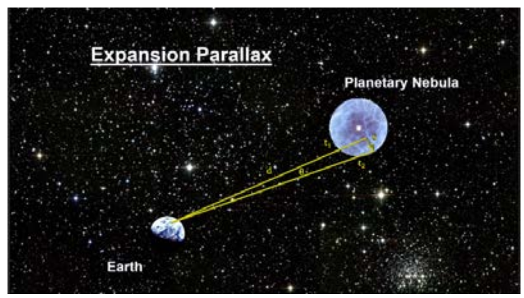
The Cat's Eye is one of the most complex planetary nebulae ever with surprisingly intricate structures including concentric gas shells, jets of high-speed gas and unusual shock-induced knots of gas.

These features made the Cat's Eye Nebula perfect for developing a new way to figure out how far away Planetary Nebula are. The fact is we don't know a lot about the distance to most of these objects. There may be as many as 25,000 Planetary Nebula in the Milky Way, but only 300 have distances that have been measured with some reasonable accuracy. This is due primarily to the nature of the nebulae themselves.

You'll recall that two of our most useful tools for figuring out 'How far away is it?" are standard candles (like Cepheids) and parallax. But because Planetary Nebula stars are surrounded by the debris of their own ejection, it is hard to get a good luminosity reading for standard candles, and equally hard to locate a good star nearby to use for parallax calculations.

Expansion Parallax

In recent years, however, observations made using the Hubble Space Telescope have allowed a new method of determining distances. All planetary nebulae are expanding, and observations several years apart and with high enough resolution can reveal the angular growth of the nebula in the plane of the sky. Using the Doppler Effect to approximate the velocity of the expanding material, we can calculate the distance the nebula expanded. With that, simple Trigonometry gives us the distance to the Cat's Eye – 3260 light years [plus or minus 877 light years].



Let:

- v = measured rate of expansion via Doppler measurements
- t = time between measurements = $(t_2 - t_1)$
- s = expansion = vt
- θ = measured angular displacement
- d = distance to nebula

We have:

$$\theta / 360 = s / 2\pi d$$

$$d = 360s / 2\pi\theta$$

For Cat's Eye:

$s = 5.18 \times 10^8$ km

$= 3.22 \times 10^8$ mi

$\theta = 3.46$ mas

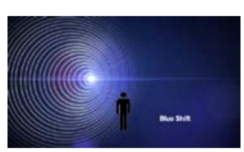
$d = 3260$ ly

Doppler Effect

We mentioned the Doppler Effect as part of this expansion parallax derivation. We also mentioned the Doppler Effect in our section on stars. So let me take a minute to go over how we measure and use this effect.

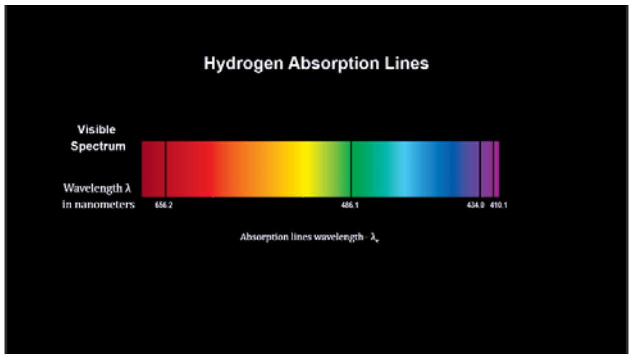
Most people have had the experience of hearing the pitch of a car horn, train whistle or ambulance siren drop as the source moved past.

As the sound source moves toward the observer, the sound waves are compressed, making the pitch of the sound higher.

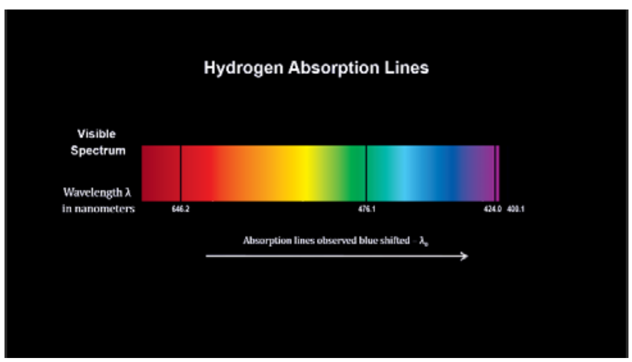


As the sound source moves away from the observer, the sound waves are stretched out, making the pitch of the sound lower.

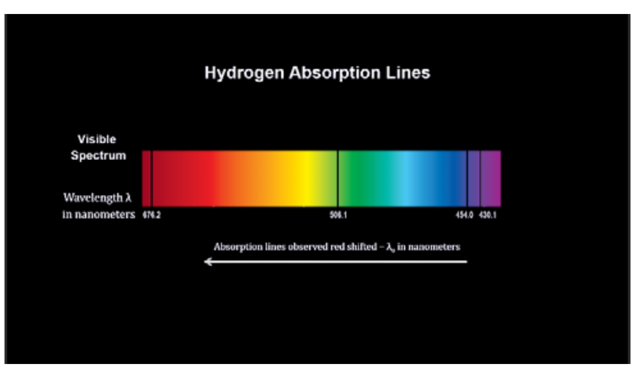
The same effect works for light. Here we have the visible spectrum from a star. Hydrogen in the stars atmosphere creates absorption lines with a unique pattern. Here's the pattern for a star at rest with respect to the observer.



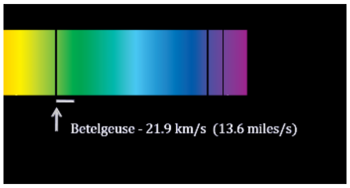
Light from an approaching star has its wavelengths shortened. We see that the lines shift to the blue. Their said to be 'blue shifted'.

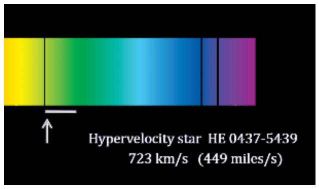


And light from a receding star has its wavelengths lengthened. We see that the lines shift to the red. Their said to be 'red shifted'.



The key to measuring the Doppler Effect is the measure the change in position of the spectral lines. The further the shift, the faster the radial velocity.





With this Doppler Effect, we can determine three important things about stars:

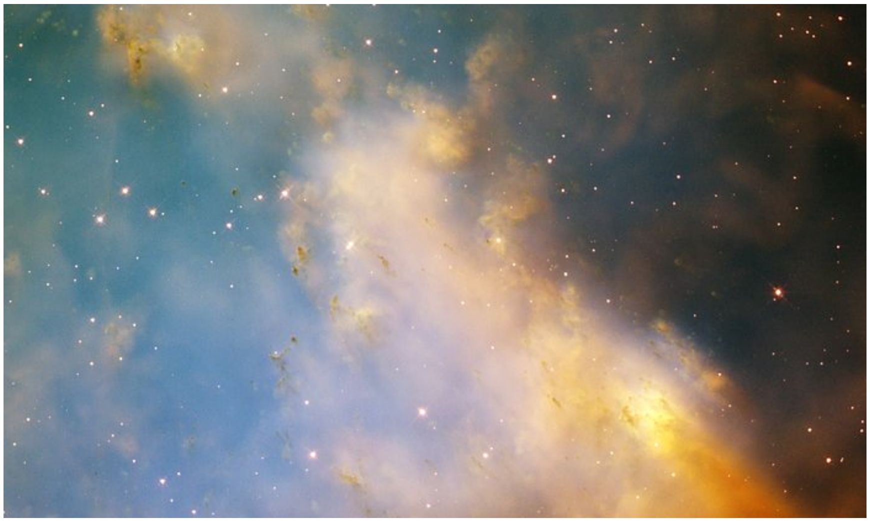
1. We can determine how fast stars and star materials are moving toward or away from us.
2. We can detect and measure the orbital motion of binary star systems.
3. We can even determine how fast a star is rotating.

Dumbbell Nebula, M27, NGC 6853 – 1,200 ly

Let's take a look at just some of the most beautiful planetary nebula scattered across the galaxy.

Here we have the Dumbbell nebula. It was the first planetary nebula ever discovered. Charles Messier found it back in 1764.

Here's a close-up taken by Hubble.



[Music: @11:47 *Boccherini, Luigi: Minuet; from String Quintet in E Op. 13 No. 5 (arr Woohouse) Academy of St. Martin in the Fields – Sir Neville Marriner, 1980/1997; from the album "The most relaxing classical album in the world…ever!"]*

<u>IRAS 18059-3211 – 1,600 ly</u>

This object is nicknamed Gomez's Hamburger. The star has already expelled large amounts of gas and dust and is on its way to becoming a colorful, glowing planetary nebula. But at this point, it is simply reflecting its light off the dust.

NGC 5189 – 1,780 ly

The intricate structure of the stellar debris forms a dramatic reverse S-shape. The structure visible within NGC 5189 is particularly dramatic. Looking at the detail, the nebula shows a series of dense knots in the clouds of gas.

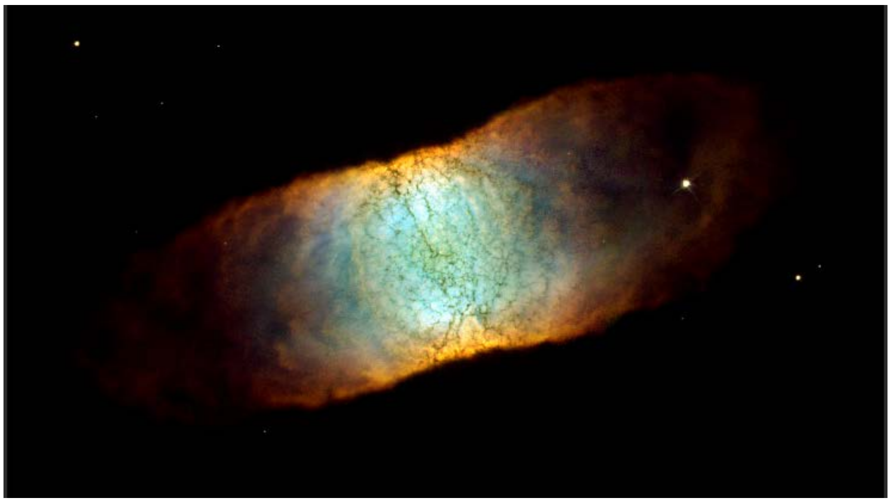
Now what's going on here is that the radiation from the dying star is carving the knots into shape, much like water flowing around a rock in a stream. And these are all pointing towards the center of the nebula. The knots are a reminder of just how vast the planetary nebula is. They might look like mere details in this image, but just like in the Helix Nebula, each and every one is the size of our entire Solar System. NGC 5189's shape is reminiscent of a lawn sprinkler, with matter being expelled from the star, which is wobbling as it rotates. Similar structures have been seen before, especially in planetary nebulae with binary stars at their centers. This is a likely explanation for 5189, but to date, only one star has been found at the nebula's centre.

Ring Nebula, M57 – 2,300 ly

Here we are zooming into the Ring Nebula, one of the earliest and most famous of all planetary nebula. As you can see, it closely resembles the Helix Nebula we covered earlier. We are looking almost directly down one the poles of the structure, with a brightly-colored barrel of material stretching away from us. From Earth's perspective, the Ring Nebula looks like a simple elliptical shape with a fuzzy boundary. But the new Hubble observations show clearly that the nebula is actually shaped more like a distorted doughnut.

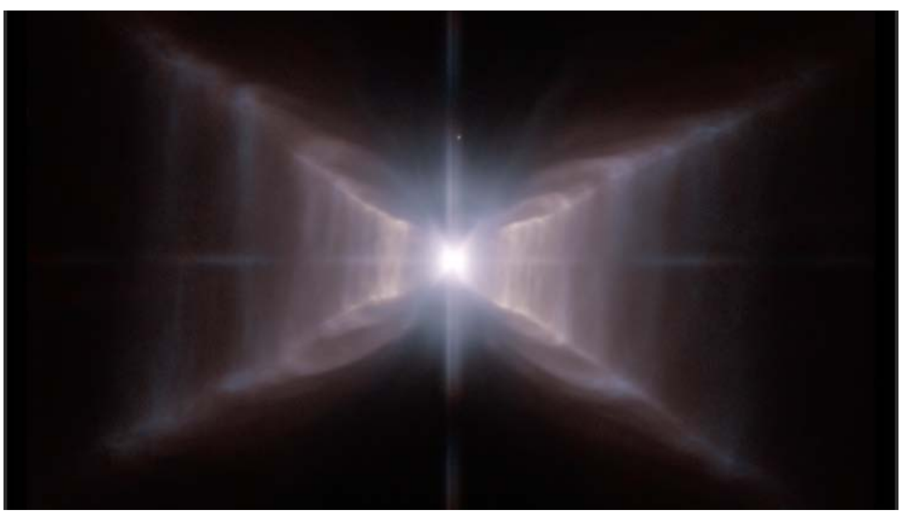
The main structure of the nebula is a broad ring of nitrogen. That's the red ring you see. The hotter gas is oxygen seen in green here and it fills the interior. What's even hotter still is helium seen here as blue oblong lobes stretching out perpendicular to the nebula's main structure and looking like a rugby ball.

IC 4406, Retina Nebula 1,900 ly



Our first Planetary Nebulae were facing the Earth so that we could see down the tube. On this one, the Retina Nebula, we are viewing the donut from the side. **[Additional info:** This side view allows us to see the intricate tendrils of dust that have been compared to the eye's retina. In this one: Oxygen is rendered blue; Hydrogen is shown as green; and Nitrogen as red.

HD 44179, Red Rectangle – 2,300 ly



The red rectangle is one of the most unusual nebulae known in our Milky Way because of its unusual rectangular shape.

Ant Nebula, Mz 3 – 3,000 ly

This unique planetary nebula resembles the head and thorax of a garden-variety ant. It has intriguing symmetrical patterns. It could be that there is a binary star system at the heart of the nebula creating the symmetrical patterns.

> ***[Music: @15:20** Rachmaninov, Sergei: Rhapsody on a Theme of Paganini – Variation 18; Cecile Ousset (Piano), City of Birmingham Symphony Orchestra / Sir Simon Rattle, 1984; from the album "The most relaxing classical album in the world…ever!"]*

Butterfly Nebula NGC 6302 – 3,800 ly

My favorite, and one of the most beautiful of all celestial objects, this planetary nebula looks like a delicate butterfly. But it is far from serene. What resemble dainty butterfly wings are actually roiling cauldrons of gas heated to more than 36,000 degrees Fahrenheit, tearing across space at more than 966,000 km/hr (that's 600,000 miles per hour).

<u>NGC 6369 – 3,500</u>

This object is known to amateur astronomers as the "Little Ghost Nebula," because it appears as a small, ghostly cloud surrounding the faint, dying central star.

<u>NGC 2440 – 3,600 ly</u>

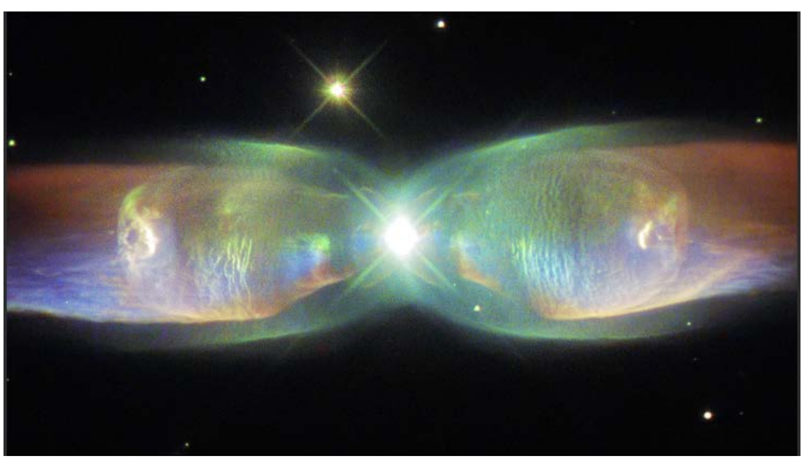
This nebula's chaotic structure suggests that the star shed its mass episodically. During each outburst, the star expelled material in a different direction. This can be seen in the two bow tie-shaped lobes.

<u>NGC 6572 – 3,500 ly</u>

This Hubble picture of NGC 6572 shows the intricate shapes that can develop as stars expel their atmosphere. You can see the central white dwarf star, the origin of the nebula - now a faint hot white dwarf.

NGC 6572 only began to shed its gases a few thousand years ago, so it is a fairly young planetary nebula. As a result the material is still quite concentrated, which explains why it is abnormally bright. [The envelope of gas is currently racing out into space at a speed of around 15 km/s (that's 9 mi/s).] As it becomes more diffuse, it will dim.

<u>Twin Jet Nebula – 4,000 ly</u>



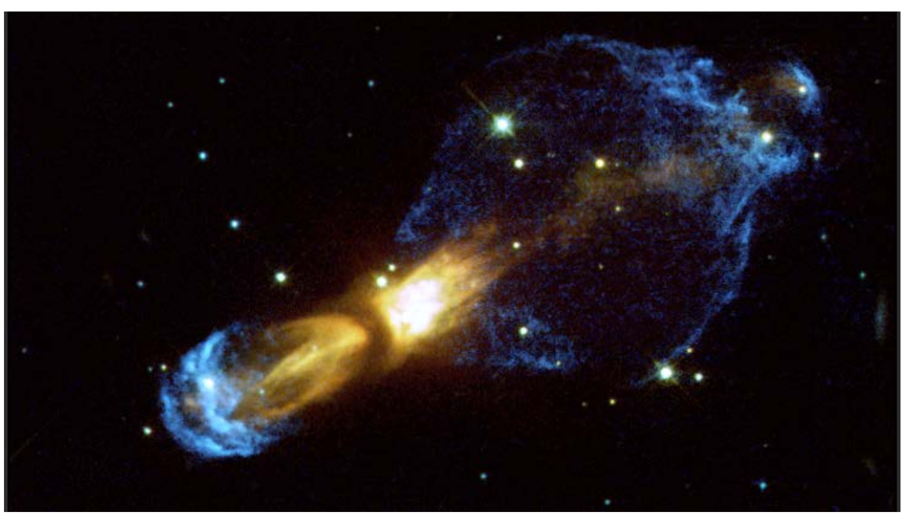
The Twin Jet Nebula, or PN M2-9, is a striking example of a bipolar planetary nebula. Bipolar planetary nebulae are formed when the central object is not a single star, but a binary system, Studies have shown that the nebula's size increases with time, and measurements of this rate of increase suggest that the stellar outburst that formed the lobes occurred just 1200 years ago.

[Music: @18:18 *Mendelssohn, Felix: Violin Concerto in E minor; Yehudi Menuhin (violin), Philharmonia Orchestra – Efrem Kurtz 1959/1997; from the album "The most relaxing classical album in the world…ever!"****]***

NGC 6153 – 4000 ly

NGC 6153 is a planetary nebula that is elliptical in shape, with an extremely rich network of loops and filaments, shown clearly in this Hubble image. However, this is not what makes this planetary nebula so interesting for astronomers.
Measurements show that NGC 6153 contains large amounts of neon, argon, oxygen, carbon and chlorine — up to three times more than can be found in our Solar System. The nebula contains a whopping five times more nitrogen than the Sun! Although it may be that the star developed higher levels of these elements as it grew and evolved, but it seems more likely that the star originally formed from a cloud of material that already contained lots more of these elements.

Calabash Nebula, OH 231+4.2 – 4,500 ly



This new, detailed, Hubble image shows a planetary nebula in the making - a proto-planetary nebula. A dying star (hidden behind dust and gas in the center of the nebula) has ejected massive amounts of gas. Parts of the gas have reached tremendous velocities of up to one-and-a-half million kilometers per hour (that's 932,000 mi/hr). **[**This nebula is also known as the Rotten Egg nebula because it has a large amount of sulfur compounds.**]**

Kohoutek 4-55 – 4,600 ly

Kohoutek 4-55 is named after its discoverer, Czech astronomer Lubos Kohoutek. **[Additional info:** You may have heard about the comet he discovered that also bears his name.**]**

Eskimo Nebula, NGC 2392 – 5,000 ly

This is nicknamed the "Eskimo" Nebula because, when viewed through ground-based telescopes, it resembles a face surrounded by a fur parka. Although this bright central region resembles a ball of twine, it is, in reality, a bubble of material being blown into space by the central star's intense "wind" of high-speed material.

NGC 6751 – 6,500 ly

NGC 6751 is strikingly unusual for planetary nebula. It looks like a giant eye. The nebula is a cloud of gas ejected several thousand years ago from the hot star visible in its center.

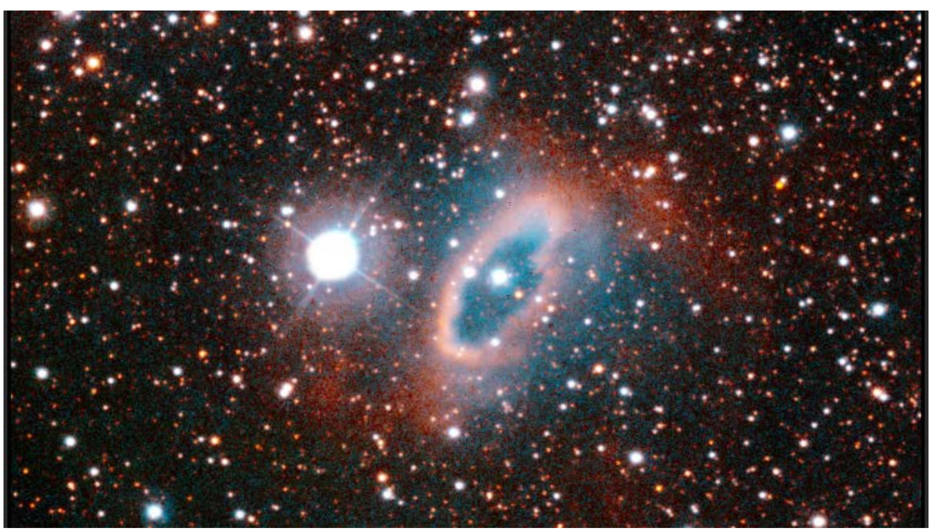
Boomerang Nebula – 5000 ly

The Hubble telescope took this image in 1998. It shows faint arcs and filaments embedded within the diffuse gas of the nebula's smooth 'bow tie' lobes. The nebula's shape appears to have been created by a very fierce 500,000 kilometers-per-hour wind blowing gas away from the dying central star (that's 310,000 mi/hr). This rapid expansion of the nebula has made it one of the coldest known regions in the Universe.

<u>Red Spider Nebula – 6,000 ly</u>

Huge waves are sculpted in this two-lobed nebula. It harbors one of the hottest stars known and its powerful stellar winds generate waves 100 billion kilometers high. The waves are caused by supersonic shocks, formed when the local gas is compressed and heated in front of the rapidly expanding lobes. The atoms caught in the shock emit the spectacular radiation seen in this image.

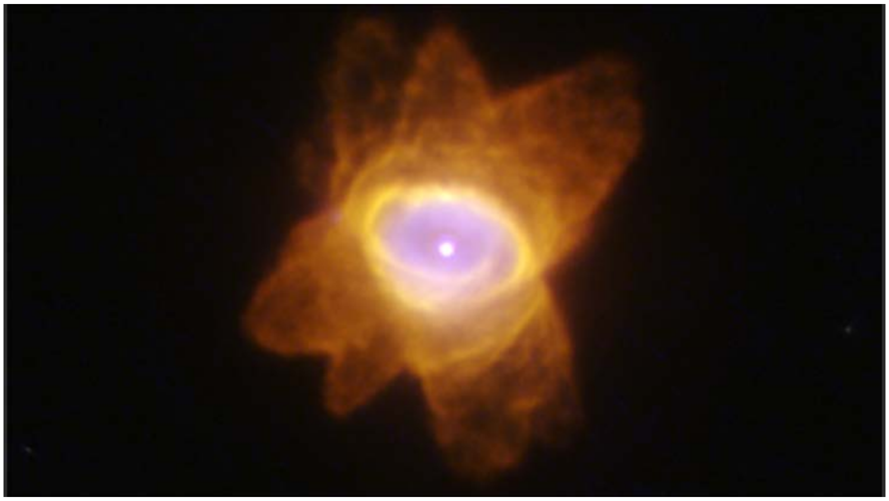
<u>SuWt 2 – 6,500 ly</u>



SuWt2, the central star is actually a close binary system where two stars completely circle each other every five days. The interaction of these stars and the more massive star that sheds material to create the nebula formed the ring structure. The burned out core of the massive companion has yet to be found inside the nebula.

> ***[Music: @22:49** Massenet, Jules: Meditation from 'Thais'; Hans Kalafusz (violin), Stuttgart Radio Symphony Orchestra / Sir Neville Marriner, 1987 EMI Electrola GmbH - from the album "The most relaxing classical album in the world…ever!"**]***

Starfish Nebula, Hen 2-47 – 6,600 ly

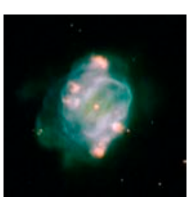


This nebula is dubbed the "starfish" because of its shape. The six lobes of gas and dust, which resemble the legs of a starfish, suggest that Hen 2-47 puffed off material at least three times in three different directions.

NGC 5315 – 7,000 ly

NGC 5315 is a chaotic-looking nebula and reveals an x-shaped structure.

[NGC 5307 – 7,900 ly

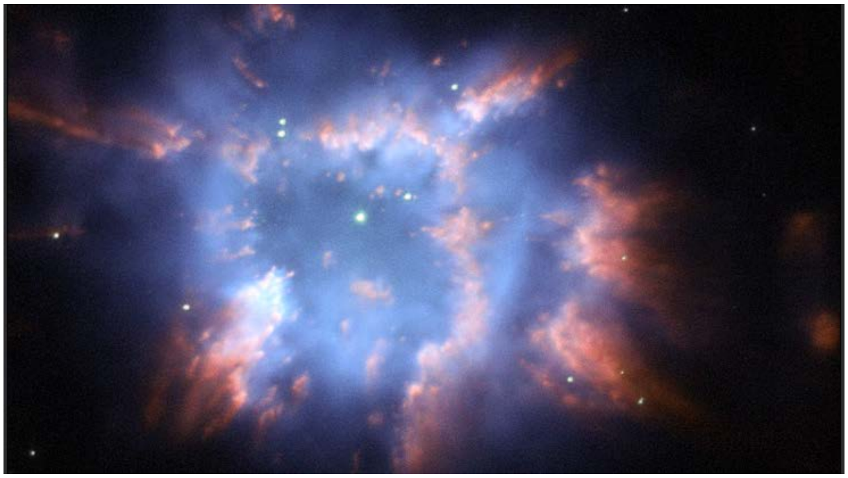


NGC 5307 displays a spiral pattern, which may have been caused by the dying star wobbling as it expelled jets of gas in different directions.]

PK 329-02.2 – 7,000 ly

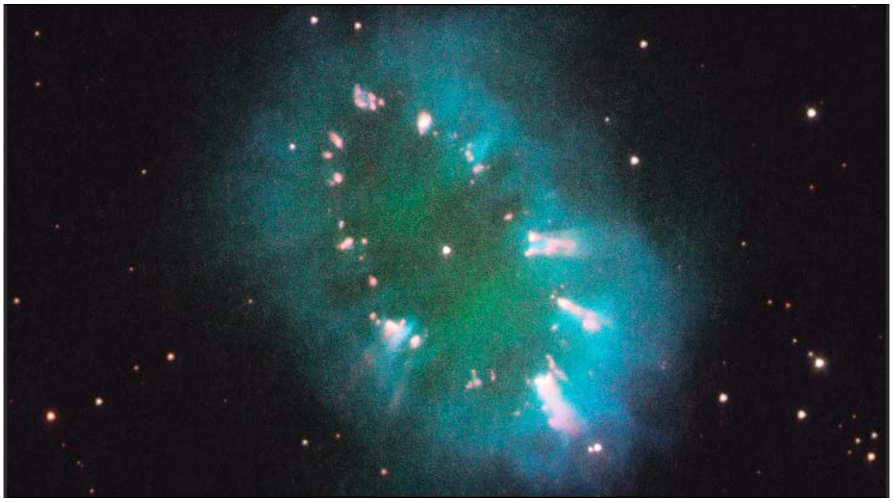
This nebula forms a winding blue cloud that perfectly aligns with two stars at its center. In 1999 astronomers discovered that the star at the upper right is in fact the central star of the nebula, and the star to the lower left is probably a true physical companion of the central star.

NGC 6326 – 11,000 ly



The Hubble Space Telescope captured this beautiful planetary nebula with glowing wisps of outpouring gas that are lit up by a central star nearing the end of its life. Planetary nebulae are one of the main ways in which elements heavier than hydrogen and helium are dispersed into space after their creation in the hearts of stars. Eventually some of this ejected material may form new stars and planets. The vivid red and blue hues in this image come from the material glowing under the action of the fierce ultraviolet radiation from the still hot central star.

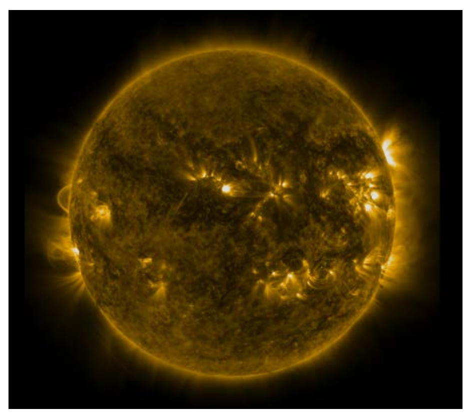
Necklace Nebula, PN G054.2-03.4 – 15,000 ly



The Necklace Nebula consists of a bright ring, measuring 12 trillion miles across, dotted with dense, bright knots of gas that resemble diamonds in a necklace. The knots glow brightly due to absorption of ultraviolet light from the central stars. Although most stars go through this process, only a few can be seen in the Milky Way. This is because over a relatively short time (millions of years), the ejected gasses get so far away from the star, that they are no longer fluorescing or reflecting light from the central dying star. Then all we see are the White Dwarfs.

Conclusion

Our Sun will end its life as one of these Planetary Nebulas. The Hubble images like these show that our Sun's fate probably will be more interesting, complex, and striking than astronomers imagined just a few years ago, but not until several billions of years from now.



Distance Ladder

In our segments on stars, we introduced a number of rungs for our cosmic distance ladder – parallax, the H-R Diagram and two standard candles – Cepheids and RR Lyrae. In this segment, we added Expansion Parallax. In our next segment, we'll add star clusters and supernova.