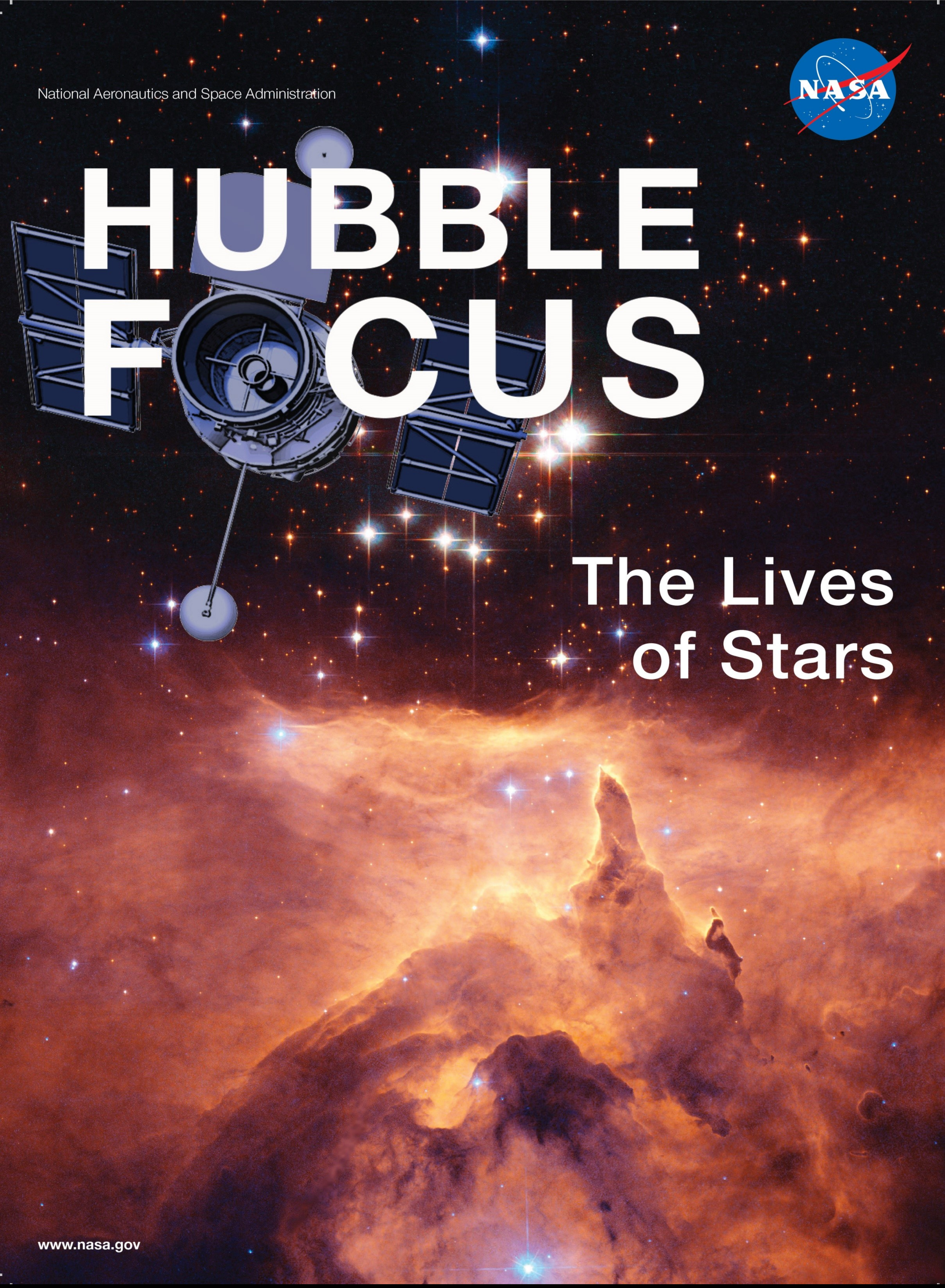
National Aeronautics and Space Administration

HUBBLE FOCUS

The Lives of Stars



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INTRODUCTION

This e-book is part of a series called *Hubble Focus*. Each book presents some of *Hubble*'s more recent and important observations within a particular topic. The subjects span from our nearby solar system out to the horizon of *Hubble*'s observable universe.

This book, *Hubble Focus: The Lives of Stars*, highlights some of *Hubble*'s recent discoveries about the birth, evolution, and death of stars. *Hubble*'s contributions are often in partnership with other space telescopes as well as those on the ground, and they build on decades of discoveries that came before *Hubble*'s launch. Its findings are helping us understand how our universe has come to be the way it is today.

This glittery spray of ancient stars, collectively called NGC 4833, is located about 22,000 light-years from Earth. It is one of more than 150 globular star clusters in our Milky Way galaxy.

Credit: ESA/*Hubble* and NASA

About the *Hubble Space Telescope*

Since its launch in 1990, NASA's *Hubble Space Telescope* has made more than 1.5 million observations, amassed a huge archive of scientific findings, and had a profound effect on all areas of observational astronomy. *Hubble* has addressed fundamental cosmic questions and explored far beyond the most ambitious plans of its builders. It has discovered that galaxies evolve from smaller structures, found that supermassive black holes are common at the centers of galaxies, verified that the universe's expansion is accelerating, probed the birthplaces of stars inside colorful nebulas, analyzed the atmospheres of extrasolar planets, and supported interplanetary missions. The rate of discovery with *Hubble* is simply unparalleled for any telescope in the history of astronomy.

Hubble observes the universe from Earth orbit, just outside our planet's atmosphere.

Credit: NASA

As NASA's first Great Observatory and the first major optical telescope in space, *Hubble* ushered in a new era of precision astronomy. The heart of the telescope is its 94.5-inch-diameter primary mirror. It is the smoothest optical mirror ever polished, with no deviations greater than one-millionth of an inch.

Operating above Earth, free from the blurring and filtering effects of our planet's atmosphere, *Hubble* can resolve astronomical objects ten to twenty times better than typically possible with large ground-based telescopes. It also can observe those objects across a range of the electromagnetic spectrum, from ultraviolet light through visible and to near-infrared wavelengths.

Hubble can detect objects as faint as 31st magnitude, which is about 10 billion times fainter than the human eye can see. The telescope can see faint objects near bright objects—an important requirement for studying the regions around stars and close to the glowing nuclei of active galaxies. Astronomers have used *Hubble*'s sharp vision to probe the limits of the visible universe, uncovering never-before-seen objects that existed not long after the birth of the universe in the Big Bang.

Hubble's view is optically stable, meaning the quality of its observing conditions never changes from day to day or even orbit to orbit. *Hubble* can revisit celestial targets with the same acuity and image quality over and over again. This is crucial for precision observations in which astronomers try to detect small changes in the light, motion, or other behavior of a celestial object.

Hubble is more technologically advanced now than it was when launched, thanks to the maintenance and upgrades provided by five space shuttle servicing missions between 1993 and 2009. *Hubble* is expected to continue operating for years to come.

Astronaut John Grunsfeld performs work on the *Hubble Space Telescope* as the first of five spacewalks during the last servicing mission in 2009.

Credit: NASA

CHAPTER 1: Star Birth and Planet Formation

For thousands of years, people believed in a static and unchanging universe. At a glance, it is easy to see why. The stars have been twinkling in our night sky longer than anyone can remember. The constellations trace their arcs across the sky in a regular, predictable way. It may seem as though the starry sky is a peaceful backdrop full of bright, unchanging beacons.

But with the *Hubble Space Telescope*, we can take a closer look and see the stunning, chaotic processes at work in the cosmos. *Hubble* can pinpoint new stars that recently burst to life from swirling clouds of gas and dust peppered throughout the galaxy. And it has shown that some of these nascent stars are ringed with dusty debris, from which planets may form.

The star-birth process is not always straightforward. Stars are often born as twins or triplets, or in even larger litters. Gravitational tussles can lead to stars or planets being kicked out of their systems. The formation process can halt somewhere in between building a planet and a star, producing intermediate objects—called brown dwarfs—that cannot truly be described as either. Young stars often exhibit violent activity that may sear their planets with harmful radiation. For over 30 years, *Hubble* has observed stars near and far to help us understand more about how they form and evolve. The studies have also helped us piece together how our own little cosmic neighborhood may have formed—our Sun, planets, and eventually us.

Hubble viewed the so-called Pillars of Creation in near-infrared light to peer inside the structure's gaseous towers, transforming them into eerie, wispy silhouettes. The image reveals three giant columns of cold gas and dust scorched by ultraviolet light from a cluster of young, massive stars in a small region of the Eagle Nebula, or M16.

Credit: NASA, ESA, and the *Hubble* Heritage Team (STScI/AURA)

This colorful image, resembling a cosmic version of an undersea world, was released to commemorate the 30th anniversary of *Hubble*'s launch. In the portrait, the giant red nebula (NGC 2014) and its smaller blue neighbor (NGC 2020) are part of a star-forming region in the Large Magellanic Cloud—a dwarf galaxy that orbits our Milky Way. The larger nebula's sparkling centerpiece is a grouping of bright, hefty stars that are each 10 to 20 times more massive than our Sun. The blue nebula was created by a solitary mammoth star 200,000 times brighter than our Sun.

Credit: NASA, ESA, and STScI

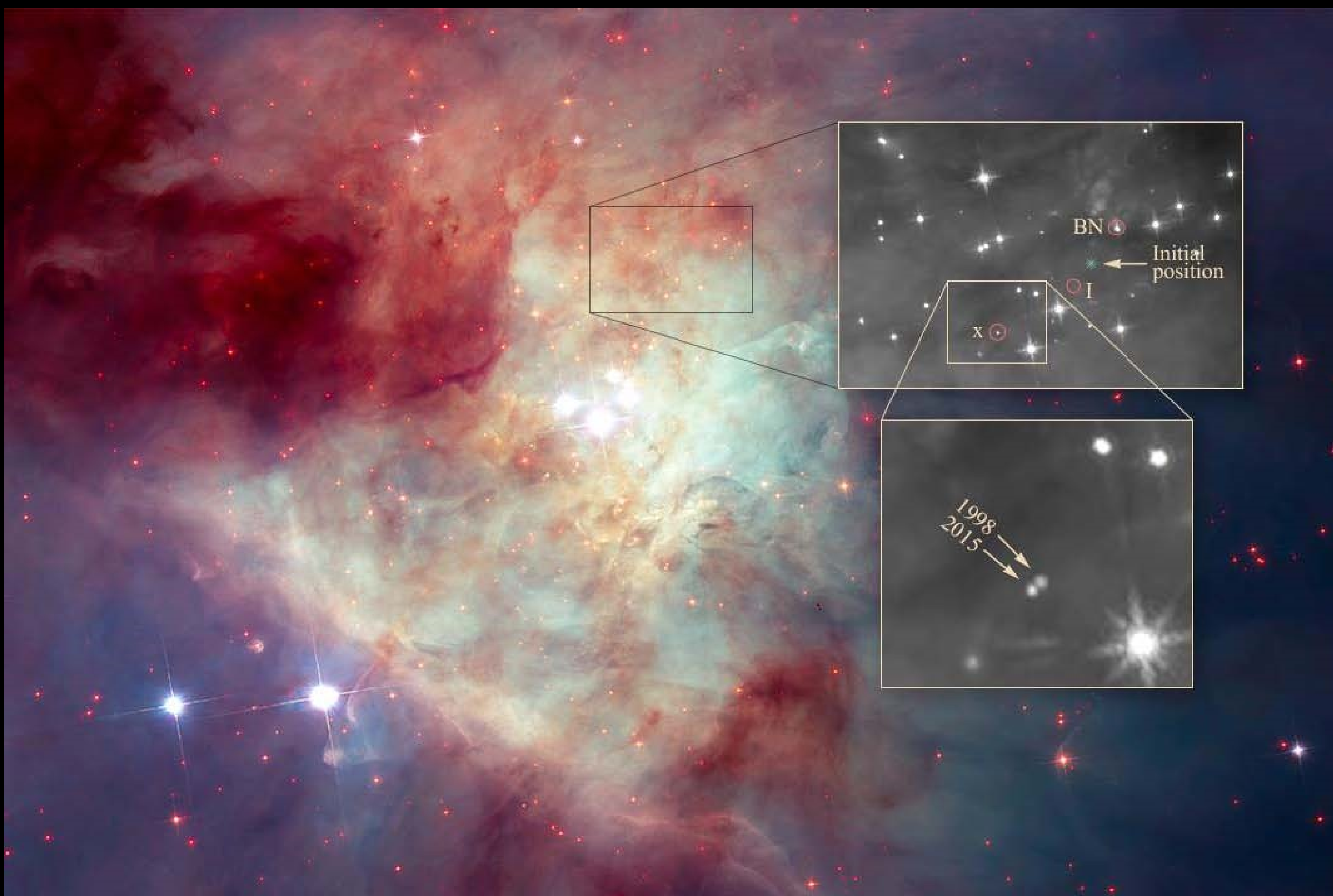
Gathering Clues to a Star System's Breakup

About 1,300 light-years away, the Orion Nebula is hosting real-life star wars. A gravitational tussle has resulted in the breakup of a young multiple-star system, sending fledgling stars flying away in different directions. The speedy, wayward stars went unnoticed for hundreds of years until recent infrared and radio observations, which could penetrate the thick dust in the Orion Nebula, picked out two of the stars. Astronomers traced both stars back to the same starting point, but the duo's combined momentum, which is propelling them away from each other, didn't add up to fully account for the stars' motion. It seemed as if a third party must have been involved in the breakup.

Hubble helped solve the missing momentum puzzle by revealing the long-suspected third member of the group. Researchers found the third star while hunting for free-floating planets using the near-infrared vision of *Hubble*'s Wide Field Camera 3. Astronomers compared these infrared images, taken in 2015, with infrared observations taken in 1998 using *Hubble*'s Near Infrared Camera and Multi-Object Spectrometer (NICMOS) and found that the star is moving about 130,000 miles per hour—much faster than the other stars in the area. Astronomers followed the newly found star's path back in time to the same location where the two previously known speeding stars once resided. All three of the runaway stars continue to move extremely fast on their way out of the nebula.

"These three stars are the youngest examples of such ejected stars. They're probably only a few hundred thousand years old."

Kevin Luhman, Penn State University



Hundreds of stars sparkle in this *Hubble* image of the Orion Nebula, taken in visible and near-infrared light, but three standout stars are shown in the upper-right inset. Labeled BN, I, and x, these wayward stars were members of the same multiple-star system before they were thrown apart following a gravitational tug-of-war. The lower-right inset shows how far star x traveled between 1998 and 2015.

Credit: NASA, ESA, K. Luhman (Penn State University), and M. Robberto (STScI)

Learn more: https://hubblesite.org/contents/news-releases/2017/news-2017-11

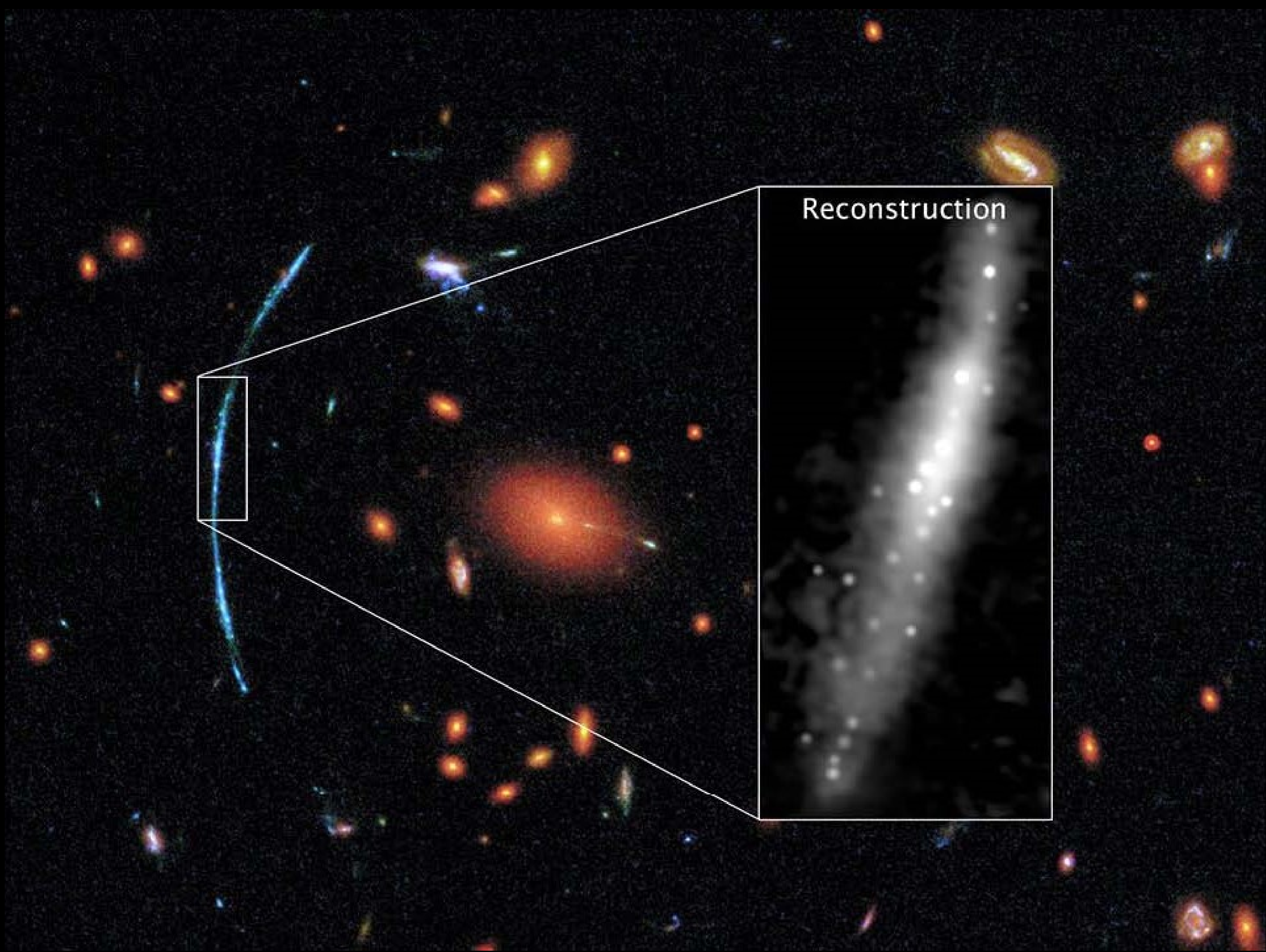
Puzzling Out Star Formation in the Early Universe

When the universe was young, stars formed at a much higher rate than they do today. *Hubble* can explore this early cosmic era by peering across billions of light-years of space to view distant galaxies. With the help of a light-bending phenomenon called gravitational lensing, *Hubble* took an even closer look to view the distant galaxy SGAS J111020.0+645950.8, alight with furious star-forming activity.

Gravitational lensing happens when the gravity from an intervening cluster of galaxies warps and magnifies light from a more distant galaxy as the light makes its way to Earth. *Hubble* used a set of these natural cosmic magnifying glasses to view a galaxy so remote that we see it as it appeared 11 billion years ago, only 2.7 billion years after the Big Bang. Researchers developed computer software to remove distortions created by the lensing and reveal the galaxy's disk as it would normally appear. Between the distortion removal and the magnification of the gravitational lens, astronomers were able to capture an image that is 10 times better than what *Hubble* could achieve on its own, showing dense clusters of brilliant, young stars in the galaxy that resemble cosmic fireworks. Theories predicted that star-forming regions in the distant, early universe were 3,000 light-years or more in size; however, the *Hubble* image revealed two dozen clumps of newborn stars that each spanned only about 200 to 300 light-years.

"When we saw the reconstructed image we said, 'Wow, it looks like fireworks are going off everywhere.'"

Jane Rigby, NASA Goddard Space Flight Center



The gravity of a giant cluster of galaxies (called SDSS J1110+6459) distorts a more distant galaxy's light, stretching it into an arc and magnifying it almost 30 times. The reconstructed image shows the disk of the distant galaxy as it would appear undistorted, revealing bright patches of young stars.

Credit: NASA, ESA, and T. Johnson (University of Michigan)

Learn more: https://hubblesite.org/contents/news-releases/2017/news-2017-27

While it appears to depict a ghoulish face, this *Hubble* image actually captures a titanic collision between galaxies. The entire system, located about 700 million light-years from Earth, is cataloged as Arp-Madore 2026-424. Each "eye" is the bright core of a galaxy, and all of the blue regions are areas where young stars have burst into life as a result of the collision.

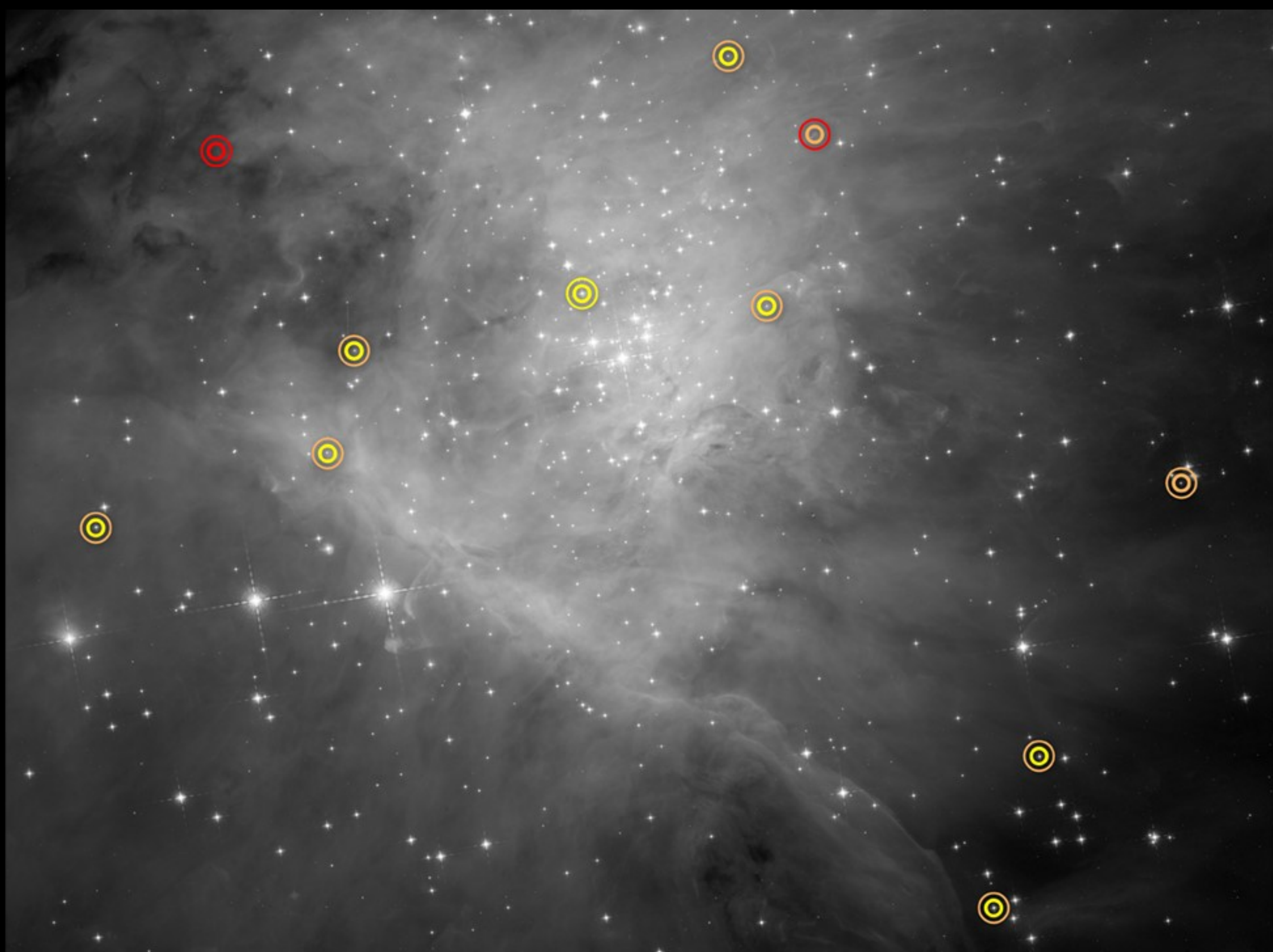
Credit: NASA, ESA, and J. Dalcanton, B.F. Williams, and M. Durbin (University of Washington)

Uncovering Brown Dwarfs in the Orion Nebula

Performing an unprecedented survey to search for small, faint objects in the Orion Nebula, astronomers used *Hubble* to uncover the largest known population of brown dwarfs. These strange celestial objects are too massive to be classified as planets, but are not massive enough to ignite as stars. Brown dwarfs provide important clues to understanding how stars and planets form, and they can be identified by the presence of water vapor in their atmospheres. Hot water vapor in the atmospheres of brown dwarfs cannot be easily detected from Earth's surface because water vapor in our own atmosphere interferes with the observations. *Hubble*'s location above Earth's atmosphere and its near-infrared vision allowed it to easily spot water on these brown dwarfs.

"Water is a signature of substellar objects. It's an amazing and very clear mark." **Massimo Robberto, Space Telescope Science Institute**

The team of researchers searched for companions to 1,200 reddish stars in an effort to locate especially small and faint objects. They found 17 candidate brown dwarf companions to red dwarf stars, one brown dwarf pair, and one brown dwarf with a planetary companion. The study also revealed three possible planets: one gravitationally linked to a red dwarf, one to a brown dwarf, and one to another planet.



Each target in this *Hubble* image identifies a pair of objects, which can be seen in the symbol's center as a single dot of light. Each color-coded circle represents a stellar object: red for a planet, orange for a brown dwarf, and yellow for a star.

Credit: NASA, ESA, and G. Strampelli (STScI)

Learn more: https://hubblesite.org/contents/news-releases/2018/news-2018-03

Capturing the Roiling Heart of a Vast Stellar Nursery

This video shows two different *Hubble* views of the star-forming Lagoon Nebula. A visible-light portrait dissolves to show the region in near-infrared wavelengths of light. Infrared observations of the cosmos allow astronomers to penetrate vast clouds of gas and dust to uncover hidden stellar gems.

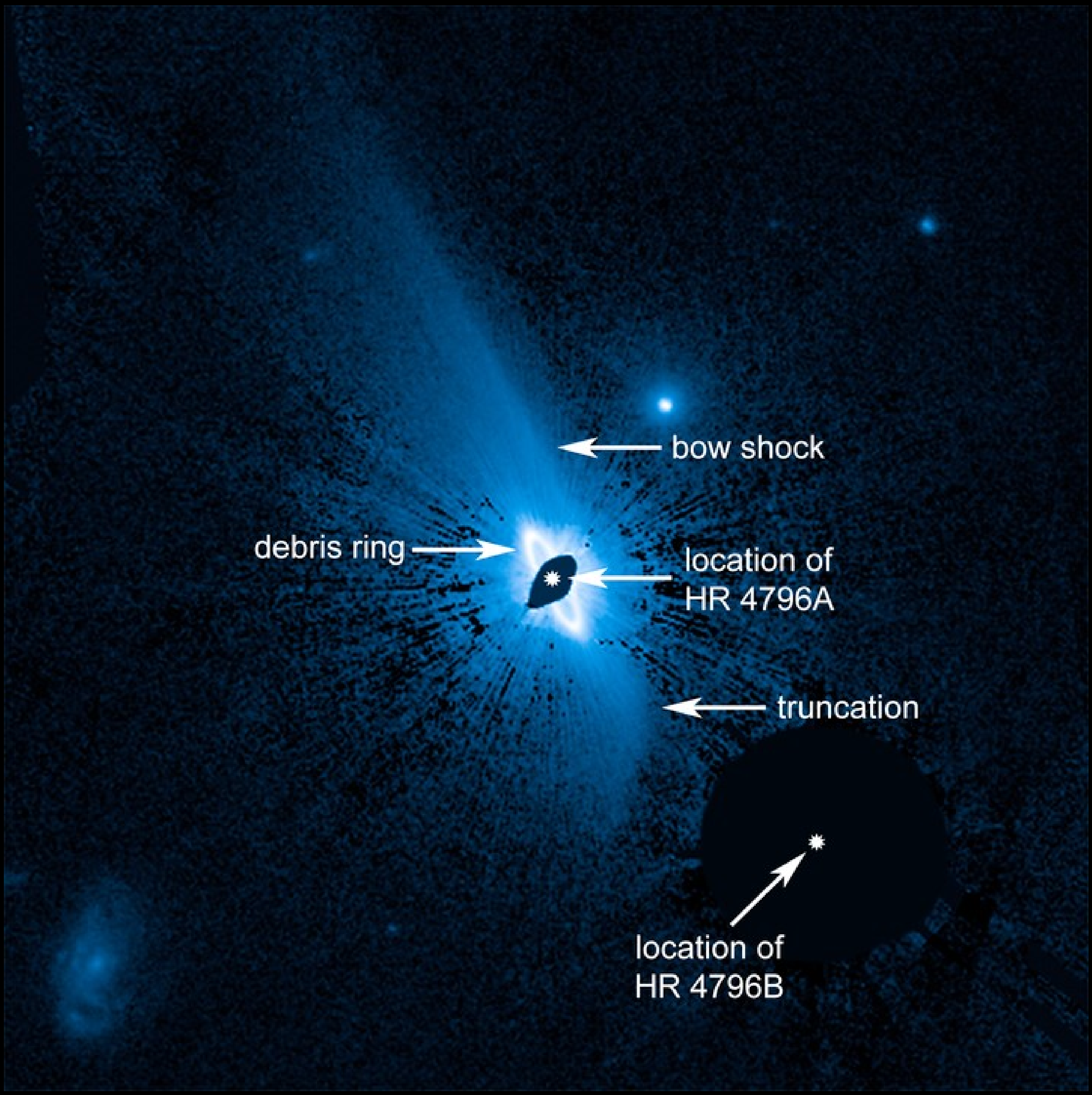
Credit: NASA, ESA, and G. Bacon (STScI)

Spotting a Huge Dusty Disk around the Young Star HR 4796A

The idea that planets form in dusty disks around stars is hundreds of years old, but astronomers only found observational evidence relatively recently. Stars are so bright that they typically render surrounding debris invisible, which hides clues about young star systems. *Hubble* has advanced our understanding of circumstellar environments by using instruments to block starlight so that dimmer features and objects near a star can be seen. Astronomers using *Hubble* previously discovered a bright, narrow inner ring of dust around a young star named HR 4796A, but new observations revealed a much more expansive dust structure enveloping the star.

HR 4796A is likely forming infant planets—a process scientists think is mostly confined to the smaller, donut-shaped ring of dust, which lies seven billion miles from the star. Collisions between the system's developing planets likely created the newly discovered dusty debris field, which spans about 150 billion miles across. The shape of the larger dust structure, which is like a much bigger, puffier donut, is truncated—it extends farther in one direction than the other. This may be a result of the host star plowing through the interstellar medium, like the bow wave from a boat crossing a lake. Or its shape may be influenced by a gravitational tug from the star's red dwarf binary companion (HR 4796B), located at least 54 billion miles from the primary star.

> "The dust distribution is a telltale sign of how dynamically interactive the inner system containing the ring is."
>
> **Glenn Schneider, University of Arizona**



The gravitational pull of an unseen giant planet may have shaped the small, bright debris ring surrounding the young star HR 4796A. Collisions among forming planets in the debris ring likely created the newly discovered, huge dust structure around the system.

Credit: NASA, ESA, and G. Schneider (University of Arizona)

Learn more: https://hubblesite.org/contents/news-releases/2018/news-2018-11

Exploring Shadows Cast by a Planet-Forming Disk around a Fledgling Star

In a stellar nursery called the Serpens Nebula, nearly 1,300 light-years away, a young star's game of shadow play reveals secrets of its unseen planet-forming disk. A ring of debris composed of dust, rock, and ice surrounds the Sun-like star called HBC 672, but it is too small and distant for even *Hubble* to see—at least directly. The disk casts a shadow approximately 200 times the length of our solar system. This shadow would be very difficult to detect in visible light due to intervening dust, but *Hubble*'s near-infrared vision allowed astronomers to peer right through the dust. Observing the so-called "Bat Shadow" provides a glimpse of what our solar system may have looked like billions of years ago, when it was only one or two million years old.

"For all we know, the solar system once created a shadow like this."

Klaus Pontoppidan, Space Telescope Science Institute

Although the type of disk that gives rise to the shadowy feature is common around young stars, the combination of an edge-on view and the surrounding nebula is rare. HBC 672 and other stars light up gas and dust in the nebula, and without the resulting contrast there could be no visible shadow. While most of the shadow is completely opaque, scientists studied its shape and color to determine the size and composition of dust grains suspended in the disk. The team discovered new information about the properties of both the nebula and the dusty disk. The puffiness of the disk, for example, implies that it is full of gas. Even more recent observations have shown that the wing-like shadows appear to be flapping. Scientists think this movement may occur because the shape of the orbiting disk is irregular, and an unseen planet may be warping it even further.

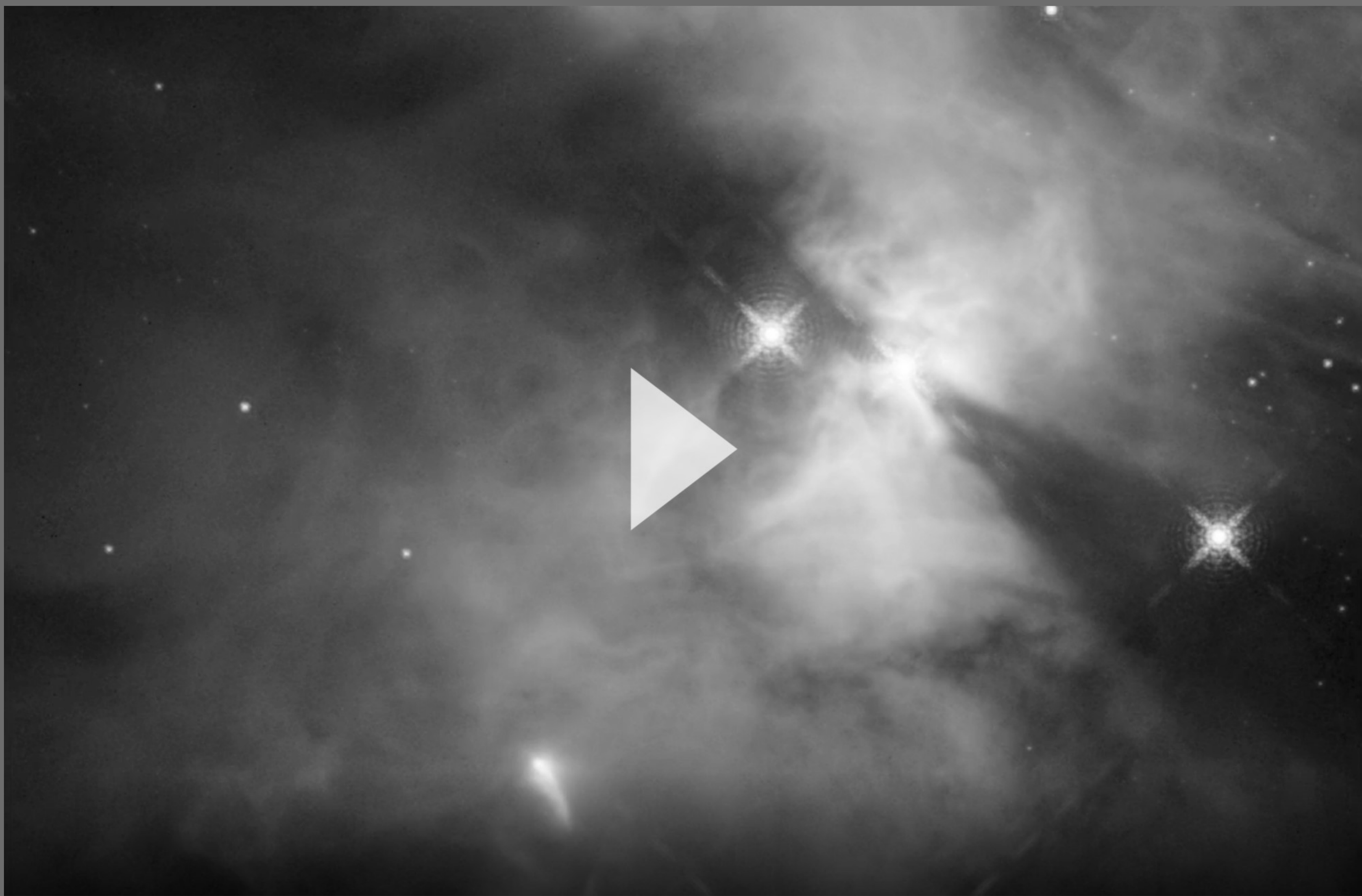
Hubble's near-infrared vision provides a view into solar system formation. In the upper right of this image, a bat-like shadow hints at the presence of a planet-forming disk around a young star.

Credit: NASA, ESA, and STScI

Learn more: https://hubblesite.org/contents/news-releases/2018/news-2018-40

https://hubblesite.org/contents/news-releases/2020/news-2020-22

Homing in on the Flapping Bat Shadow



Using its near-infrared vision, *Hubble* captured a glimpse of a young star's game of shadow play. The star, called HBC 672, is surrounded by a planet-forming disk, which blocks some of the star's light and casts a bat-like shadow on the surrounding nebula. This video, comparing two images taken approximately a year apart, shows the "flapping" of the bat shadow's wings. This motion is most likely caused by the shadow of a saddle-shaped orbiting disk, with two peaks and two dips. The disk may also be flared, like bell-bottom pants or a trumpet.

Credit: NASA, ESA, and K. Pontoppidan and J. DePasquale (STScI)

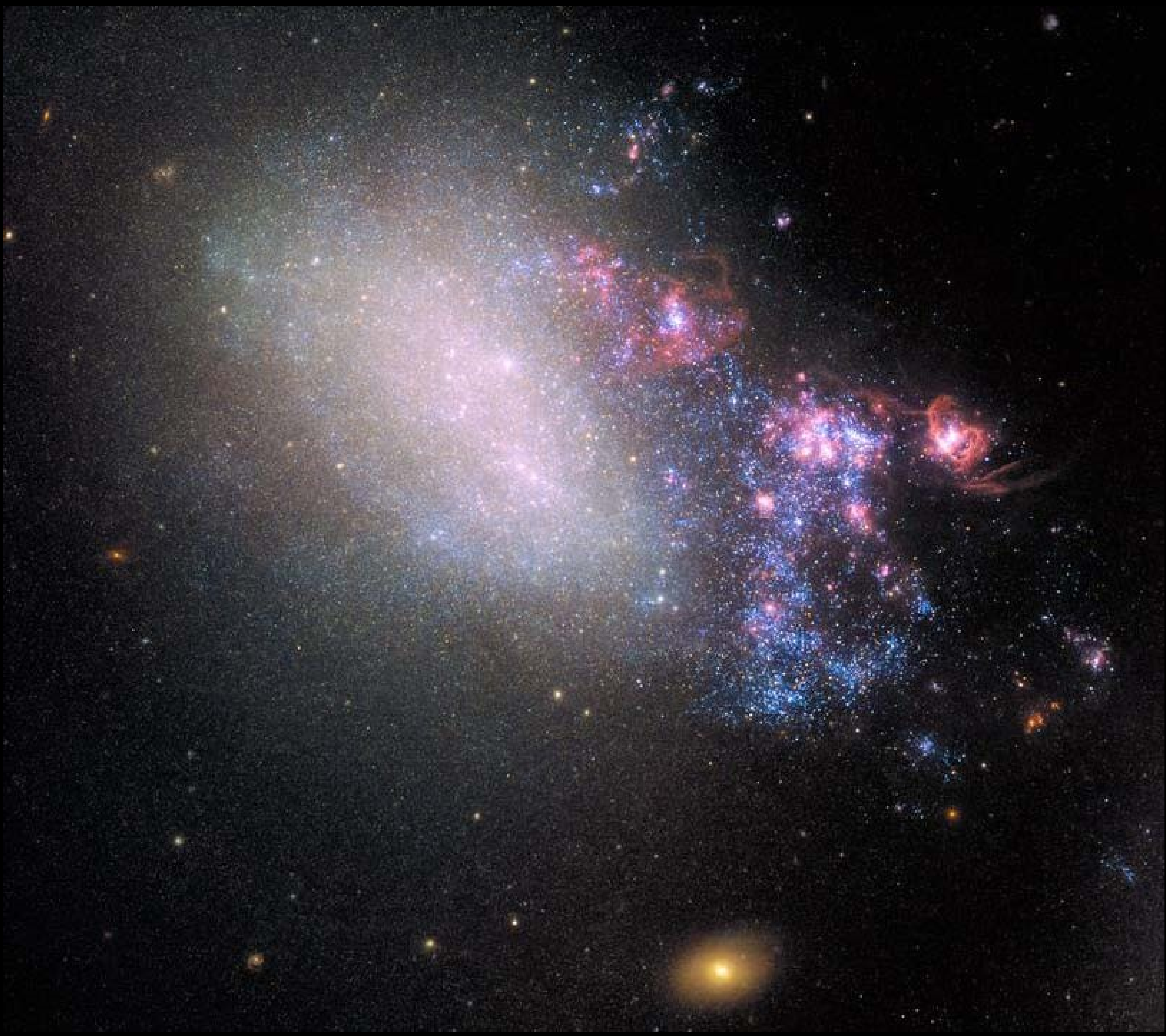
Watching Stars Burst into Life from a Close Galactic Encounter

Galaxies are colossal island universes that seldom interact with each other, but when they do it can trigger a flurry of new star birth. *Hubble* viewed the irregular galaxy NGC 4485 to study the aftermath of a glancing blow between galaxies. The observation revealed one side of the galaxy ablaze with star formation, shown in a myriad of young blue stars and star-incubating pinkish nebulas. The other side, however, appears intact and contains hints of the galaxy's previous spiral structure.

NGC 4485 and its combatant galaxy, NGC 4490, sideswiped each other millions of years ago. Rather than destroying either galaxy, the chance encounter spawned a new generation of stars, and presumably planets. The gravitational taffy pull caused by their close encounter created rippling patches of higher-density gas and dust within both galaxies, which sparked a burst of star formation. Such interactions were more common billions of years ago, when the universe was smaller and galaxies were closer together. *Hubble*'s observation not only provided further insight into the complexities of galaxy evolution—it also opened a window to the universe's distant past, when more frequent titanic collisions led to stellar renewal and birth.

"Observing the star-forming 'tail' of NGC 4485 reveals much about what can happen when galaxies actively form stars."

Tim Roberts, Durham University



When galaxies collide, it can trigger the birth of new generations of stars and planets. *Hubble* observed the galaxy NGC 4485 to view the fallout from a glancing blow from another galaxy. The image provides further insight into the complexities of galactic evolution.

Credit: NASA and ESA; Acknowledgment: T. Roberts (Durham University, UK), D. Calzetti (University of Massachusetts) and the LEGUS Team, R. Tully (University of Hawaii), and R. Chandar (University of Toledo)

Learn more: https://hubblesite.org/contents/news-releases/2019/news-2019-30

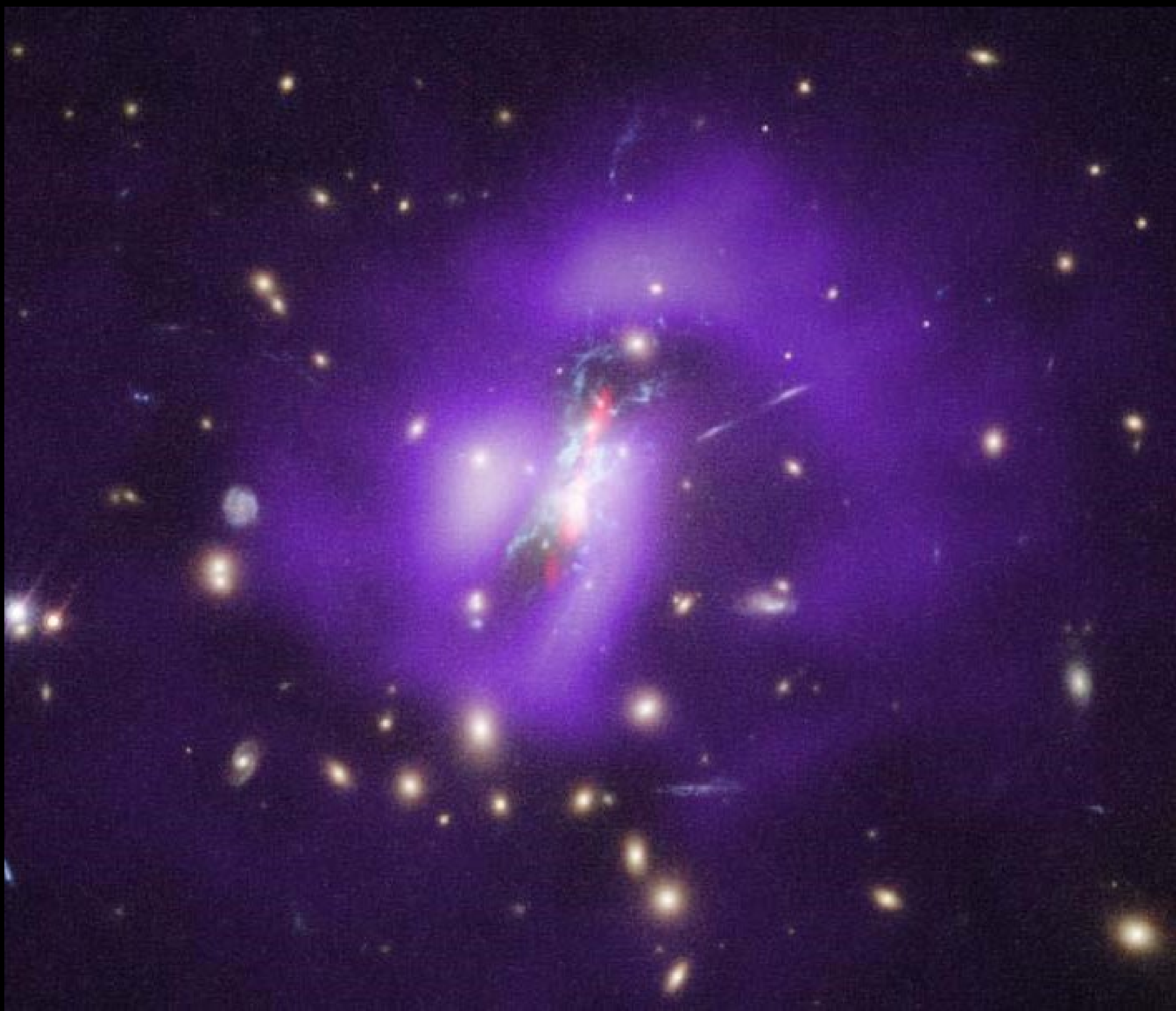
Observing Star Birth Fueled by a Supermassive Black Hole

In 1997, a *Hubble* census revealed that supermassive black holes inhabit the hearts of nearly every galaxy in the universe. These central black holes typically hinder star formation by pumping out jets of energy, keeping interstellar gas too warm to condense and form stars. However, astronomers using the combined power of *Hubble*, NASA's *Chandra X-ray Observatory*, and the Very Large Array (VLA) radio observatory in New Mexico have now discovered a black hole that is actually fueling a whirlwind of star birth in a cluster of galaxies.

The stellar turbo boost in this collection of galaxies, called the Phoenix cluster, is apparently linked to jets emitted by a black hole that lies in the middle of a galaxy at the center of the cluster. The jets are less energetic than most black hole jets are. Instead of the jets pumping up the gas temperature, the gas loses energy as it glows in X-rays and cools to where it can form large numbers of stars at a breathtaking pace—about 500 times faster than in our Milky Way galaxy. The new *Hubble* observations also showed that about 10 billion solar masses of cool gas are located along filaments leading toward the black hole.

"This cluster demonstrates that, in some instances, the energetic output from a black hole can actually enhance cooling, leading to dramatic consequences."

Michael McDonald, Massachusetts Institute of Technology



This composite image combines data from the *Chandra X-ray Observatory*, *Hubble*, and the Very Large Array (VLA) radio observatory. X-rays from *Chandra* depict hot gas in purple, and radio emission from the VLA features jets in red. Visible light from *Hubble* shows galaxies in yellow and filaments of cooler gas where stars are forming in light blue.

Credit: NASA, ESA, and NRAO

Learn more: https://hubblesite.org/contents/news-releases/2019/news-2019-44

CHAPTER 2: Star Death

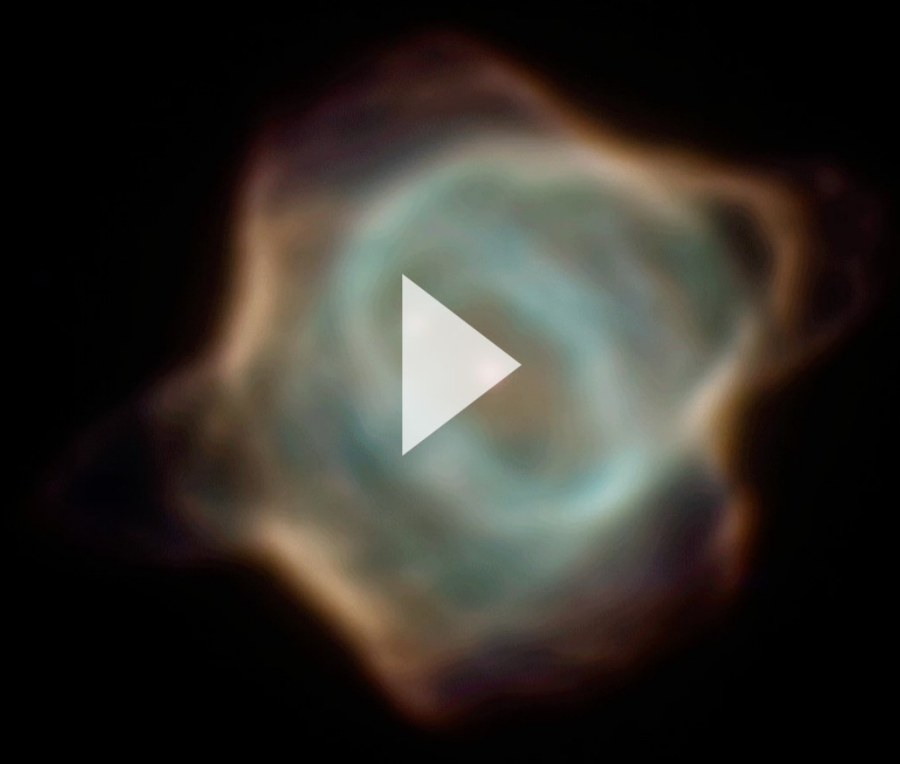
Stars live such long lives that it seems like they exist outside of time, immune to the effects of aging. But stars aren't forever; just as new ones are bursting into life on a regular basis, some run out of fuel every day. What happens next depends on the star's mass—a fate usually sealed at birth.

When a star with about the same amount of mass as the Sun runs out of fuel, it becomes unstable and expands as it puffs its outer layers of gas away into space. Our middle-aged Sun has about five billion years left before that happens. When it does, the Sun will swell to become a red giant star. After it loses its outer layers, only a small, hot core called a white dwarf will be left behind. The white dwarf will eventually fade out. Until then, the gaseous debris surrounding the white dwarf fluoresces as it expands out into the cosmos.

More massive stars are doomed to die in cataclysmic explosions called supernovas. The cores of these stars collapse until all of the protons and electrons are crushed together into neutrons. If the core is between about one and three times the mass of the Sun, the collapse stops there, leaving behind a neutron star. Stars with higher masses continue to collapse to form black holes.

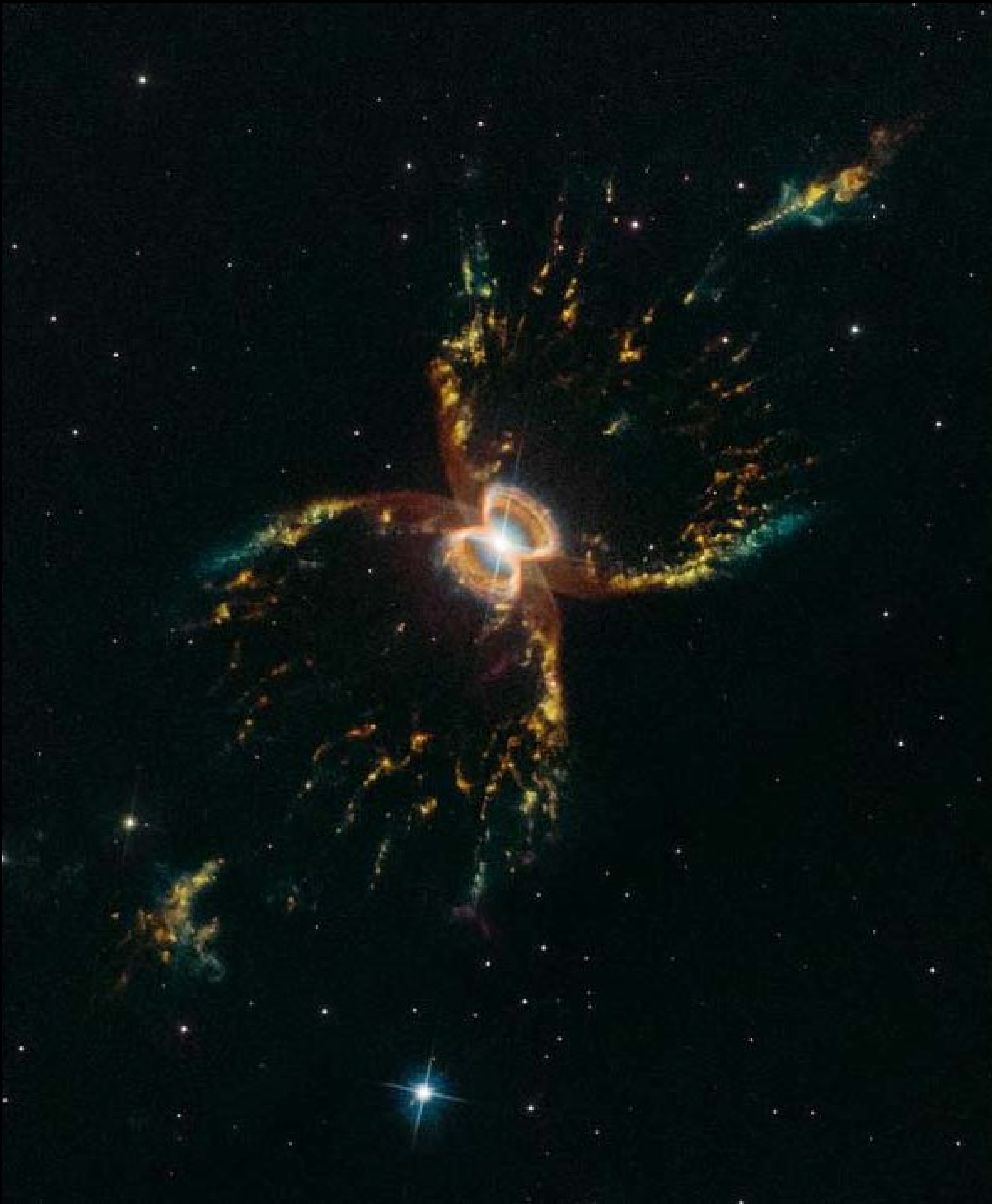
Sometimes a star can steal material from a close neighbor, increasing its mass and changing its fate.

However a star dies, it plays an important role in cosmic evolution. Whether a small star sloughs off its outer layers gently or a massive star blasts material out in a supernova, the deaths of stars seed the universe with new elements. The ejected material may be destined to be recycled into later generations of stars and planets—and, perhaps, living things.



This visualization transitions between two *Hubble* images taken in 1996 and 2016 of the planetary nebula Hen 3-1357, nicknamed the Stingray Nebula. It illustrates how drastically the nebula changed over the course of two decades. In *Hubble*'s 1996 observation, filaments and tendrils of gas glow bright blue at the nebula's center. However, *Hubble*'s 2016 observation shows a much dimmer nebula lacking its former wavy edges.

Credits: NASA, ESA, B. Balick (University of Washington), M. Guerrero (Instituto de Astrofísica de Andalucía), and G. Ramos-Larios (Universidad de Guadalajara), and J. DePasquale (STScI)



A pair of stars are putting on a light show in the Southern Crab Nebula. While both were once stars like our Sun, they are in very different stages of their lives. One has run out of fuel and expanded to become a red giant star, while the other has already collapsed into a white dwarf. The red giant is now casting off its outer layers, and some of this material is readily pulled in by the white dwarf's gravity. Scientists think the nebula's glowing "legs"—the two large, C-shaped arcs emanating from the center of the nebula—are places where the red giant's outflow slams into surrounding interstellar gas and dust.

Credit: NASA, ESA, and STScI

Finding Comet Pollution in a White Dwarf's Atmosphere

Hubble observed a white dwarf—the leftover core of a Sun-like star that exhausted its nuclear fuel—and found the best evidence yet of the remains of a comet-like object polluting the dead star's atmosphere. As many as 25 to 50 percent of white dwarfs are known to host infalling debris from rocky, asteroid-like objects, but bodies made of icy, comet-like material had never been observed in a white dwarf's atmosphere before. Astronomers used *Hubble* to detect and study the debris of the icy object. Using the ultraviolet vision of *Hubble*'s Cosmic Origins Spectrograph (COS), the team was able to make measurements that are very difficult to obtain from the ground. They found that the object that entered the white dwarf's atmosphere is chemically similar to Halley's Comet, but 100,000 times more massive and with much more water. It is also rich in the elements essential for life, including nitrogen, carbon, oxygen, and sulfur. Astronomers used the W. M. Keck Observatory in Hawaii to detect additional elements in the white dwarf's atmosphere, including calcium, magnesium, and hydrogen.

The findings indicate that there may be a belt of comet-like bodies, similar to our solar system's Kuiper Belt, orbiting the white dwarf. These icy bodies apparently survived throughout the history of the star's evolution and demise. The results also suggest the presence of unseen, surviving planets whose gravitational influence may perturb the orbits of the icy bodies, sometimes sending them on paths toward the white dwarf. The burned-out star also has a stellar companion, which may disturb objects in the belt.

"Nitrogen is a very important element for life as we know it. This particular object is quite rich in nitrogen, more so than any object observed in our solar system."

Siyi Xu, European Southern Observatory

This artist's illustration paints the cosmic scene of a massive, comet-like object falling toward a white dwarf. The *Hubble* observations that this image is based on provide evidence that icy bodies are present in planetary systems outside our own.

Credit: NASA, ESA, and Z. Levy (STScI)

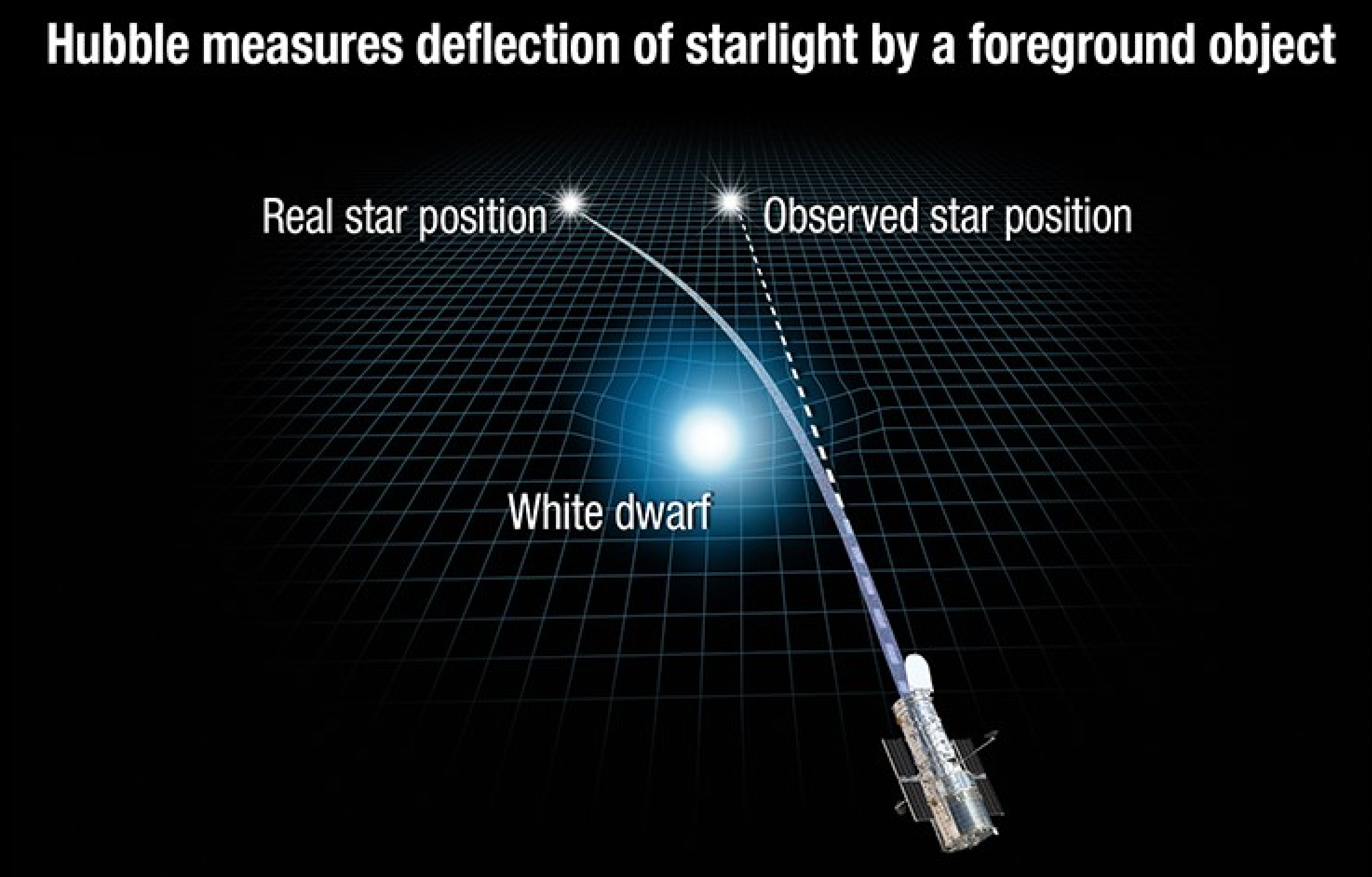
Learn more: https://hubblesite.org/contents/news-releases/2017/news-2017-09

Repurposing a Century-Old Experiment to Find a White Dwarf's Mass

In 1915, Albert Einstein proposed the revolutionary idea that massive objects warp space. This theory was verified by an experiment four years later when a team led by British astronomer Sir Arthur Eddington studied a solar eclipse. They measured how much the Sun's gravity deflected the image of a background star as its light grazed the eclipsed Sun. *Hubble*'s sharp vision has recently allowed us to view the same gravitational warping phenomenon produced by a white dwarf, instead of the Sun.

Hubble observed the nearby white dwarf Stein 2051 B as it passed in front of a distant background star. During the close alignment, the white dwarf's gravity bent the much fainter light from the background star, making the star appear offset by about 2 milliarcseconds from its actual position. This deviation is so small that it is equivalent to observing an ant crawl across the surface of a quarter from 1,500 miles away. Measuring how much the background star's light was deflected allowed astronomers to determine the white dwarf's mass, since more mass creates a larger deflection. The findings confirmed a theory describing the relationship between a white dwarf's mass and size, and provided insight into the internal composition of these dead stars.

> "Measuring the extremely small deflection is like trying to see a firefly move next to a light bulb."
>
> **Jay Anderson, Space Telescope Science Institute**



Hubble's observations of a white dwarf revealed how it warps space as it curved the light of a distant star behind it. This illustration shows how the stellar alignment shifted the apparent position of the farther star. Astronomers used this light-bending phenomenon to learn about the white dwarf's mass and composition.

Credit: NASA, ESA, and A. Feild (STScI)

Learn more: https://hubblesite.org/contents/news-releases/2017/news-2017-25

Zooming in on Shrapnel from an Exploded Star

The Veil Nebula is one of the most spectacular supernova remnants in the sky, extending 110 light-years across and covering an area of sky six times larger than the full Moon. This visualization flies across a small portion of the nebula photographed by *Hubble*, covering just 5 light-years.

Credit: NASA, ESA, and F. Summers, G. Bacon, Z. Levay, and L. Frattare (Viz 3D Team, STScI); Acknowledgment: NASA, ESA, and the *Hubble* Heritage Team (STScI/AURA)

Searching for the Stellar Survivor of a Supernova Explosion

When Sun-like stars run out of fuel, they typically end their lives relatively peacefully, gradually becoming compact white dwarfs. In some cases, however, interactions between a white dwarf and a companion star result in a Type Ia supernova explosion. These supernovas have a predictable brightness that helps astronomers measure the distances to their host galaxies and then infer the expansion rate of the universe, and led to the discovery of dark energy. However, the cause of Type Ia supernovas remains a mystery. Scientists suspect that they either occur when two white dwarfs collide or when a single white dwarf siphons material from a companion star. If the second theory is correct, the white dwarf's companion star should be left behind.

Astronomers used *Hubble* to scour the gauzy remains of a Type Ia supernova in a neighboring galaxy for a leftover star. The search revealed a possible candidate—a Sun-like star that might have been associated with the supernova. Further investigations could show whether this star is truly the culprit behind the white dwarf's fiery demise.

"*Hubble's* detailed view gives us exquisite forensic evidence for the cause of this fantastic explosion."

Jennifer Wiseman, NASA Goddard Space Flight Center

The oddly shaped gas cloud near the top center of this *Hubble* image, which combines visible and near-infrared light, was produced by a Type Ia supernova explosion. It is located 160,000 light-years from Earth in a neighboring dwarf galaxy called the Large Magellanic Cloud. Astronomers studying the supernova's remnant, called SNG 0509-68.7 or N103B, found a star that might be linked to the original explosion.

Credit: NASA, ESA, and Y.-H. Chu (Academia Sinica, Taipei)

Learn more: https://hubblesite.org/contents/news-releases/2017/news-2017-16

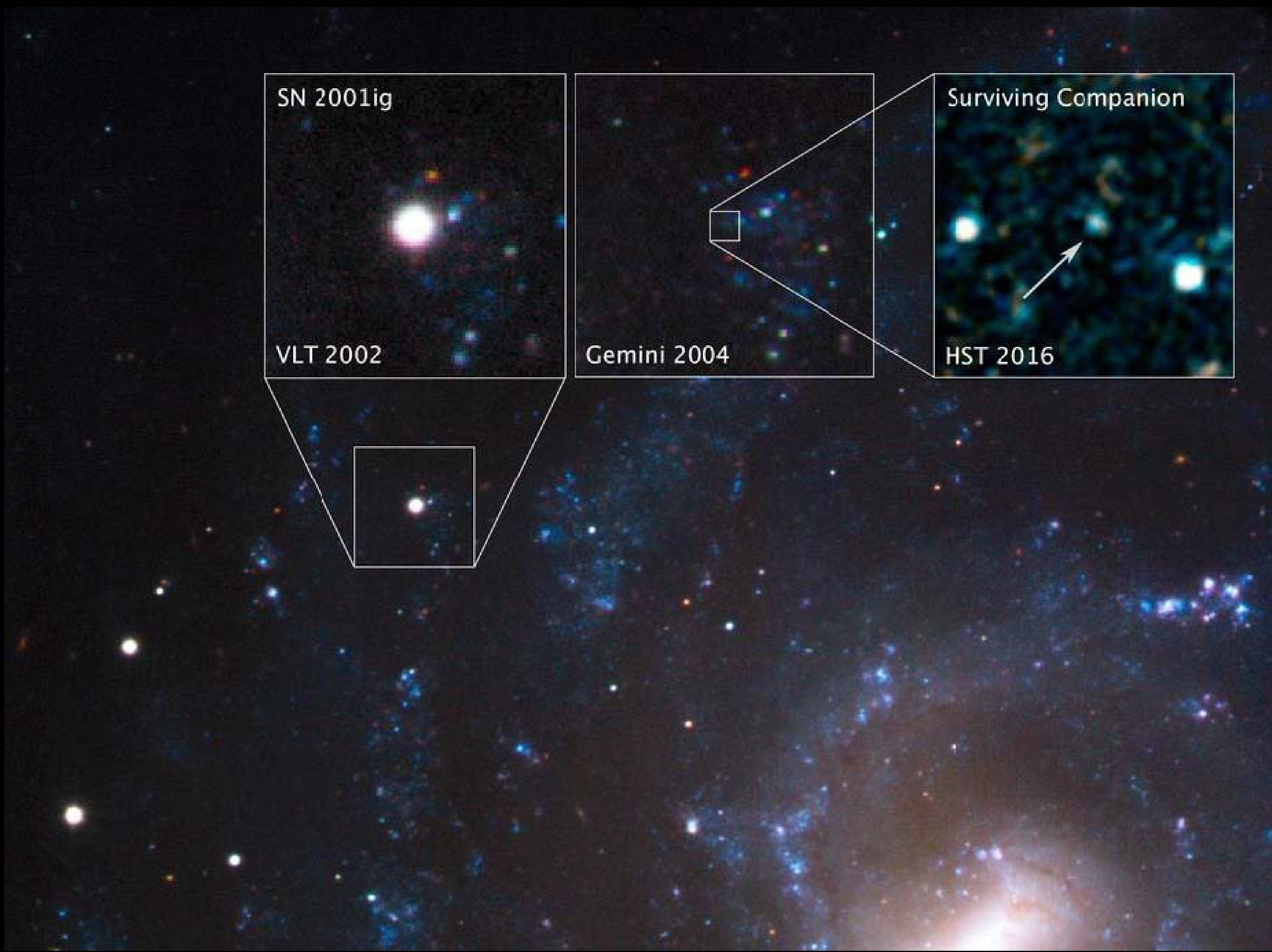
Exposing a Supernova's Companion as a Stellar Thief

Massive stars are rarely born alone—they typically have a companion. The sister stars revolve around each other, and sometimes their orbits bring them close together. During near encounters, they can interact and transfer material. Sometimes this seemingly peaceful cosmic dance has violent consequences: one of the stars may explode. *Hubble* captured the first confirmed image of a surviving companion star in the fading afterglow of a star that exploded. The observation provided the most compelling evidence yet that some supernovas originate in double-star systems.

Scientists think the surviving companion was no innocent bystander to the explosion. It likely siphoned off almost all of the hydrogen from the doomed star's stellar envelope—the region around the star that transports energy from its core to its atmosphere. Millions of years before the supernova, this thievery created an instability that caused the primary star to periodically blow off shells of hydrogen gas. The resulting explosion is categorized as a Type IIb supernova. Only *Hubble* could provide the exquisite resolution and ultraviolet vision astronomers needed to find and photograph the surviving companion.

"We were finally able to catch the stellar thief, confirming our suspicions that one had to be there."

Alex Filippenko, University of California, Berkeley



Astronomers focused *Hubble* on a fading supernova explosion about 40 million light-years away in search of a surviving binary companion. They pinpointed and photographed the star, providing the best evidence yet that some supernovas originate in double-star systems.

Credit: NASA, ESA, S. Ryder (Australian Astronomical Observatory), and O. Fox (STScI)

Learn more: https://hubblesite.org/contents/news-releases/2018/news-2018-20

Visualizing a Light Echo around an Exploded Star

This video sequence takes the viewer into the starburst galaxy M82, where a shell of light surrounding an exploding star is moving through interstellar space. A supernova produced a burst of light that was first observed in January 2014. Nearly three years later, astronomers saw light from the blast reverberating off of interstellar dust clouds—an effect called a light echo.

Credit: NASA, ESA, G. Bacon, J. DePasquale, and Z. Levay (STScI), Acknowledgment: Y. Yang (Texas A&M/Weizmann Institute of Science)

Finding the Elusive Star behind a Supernova

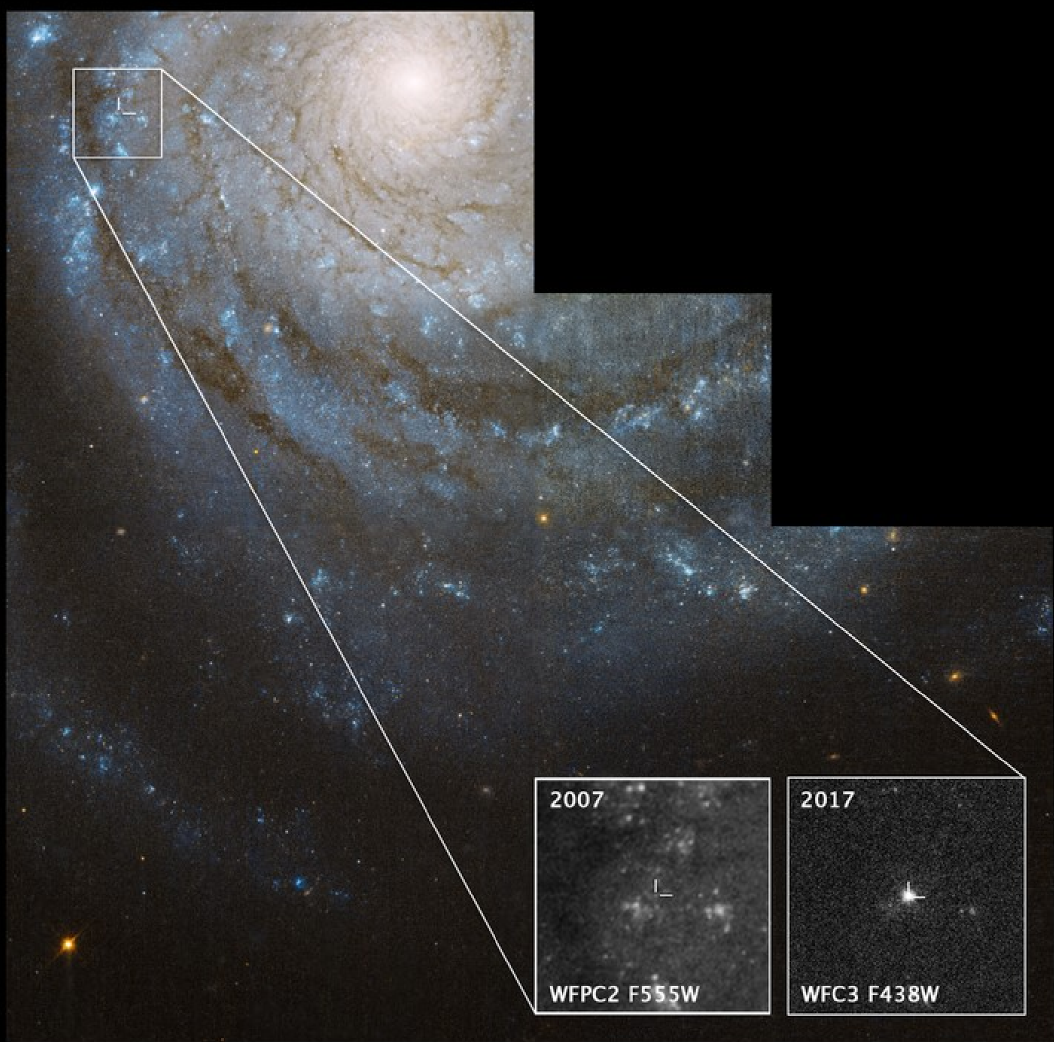
The explosive end to a massive star's life is one of the most powerful blasts in the universe. Supernovas involve conditions so intense that atoms fuse together to form new elements, which are then strewn throughout the galaxy. New stars and even planetary systems can form from these building blocks. Astronomers have long sought to understand supernovas and their doomed progenitor stars better, but some are more difficult to study than others. Type Ic supernovas have been especially elusive. These explosions stem from stars more than 30 times the mass of our Sun that lose their hydrogen and helium layers before their cataclysmic deaths.

Researchers thought the hefty stars that explode as Type Ic supernovas should be easy to find since they are big and bright, but all of their searches for such progenitor stars came up empty. In 2017, their fortune turned—they witnessed a nearby star ending its life as a Type Ic supernova. Teams of researchers searched *Hubble*'s archive of images and found the star that produced the supernova in pre-explosion photos taken in 2007. Analysis of the extremely hot, blue star suggested two possibilities for its identity.

It may have been a double-star system, or a single star between 45 and 55 times the mass of our Sun. In the former scenario, one of the stars would have between 60 and 80 times our Sun's mass and the other roughly 48 solar masses. The stars would have orbited each other closely and interacted, with the more massive star ultimately stripped of its hydrogen and helium layers by its companion. Future observations of the faded supernova using *Hubble* and the *James Webb Space Telescope* could reveal whether a possible companion star remains.

"If we can disentangle these two scenarios for producing Type Ic supernovas, it will impact our understanding of stellar evolution and star formation."

Ori Fox, Space Telescope Science Institute



When astronomers saw a Type Ic supernova in the spiral galaxy NGC 3938, they turned to *Hubble*'s image archive to find the star that produced the explosion. The 2007 inset shows the location of the progenitor star. The bright object in the 2017 inset is a close-up image of the supernova, taken shortly after astronomers saw light from the stellar blast.

Credit: NASA, ESA, S. Van Dyk (Caltech), and W. Li (University of California)

Learn more: https://hubblesite.org/contents/news-releases/2018/news-2018-47

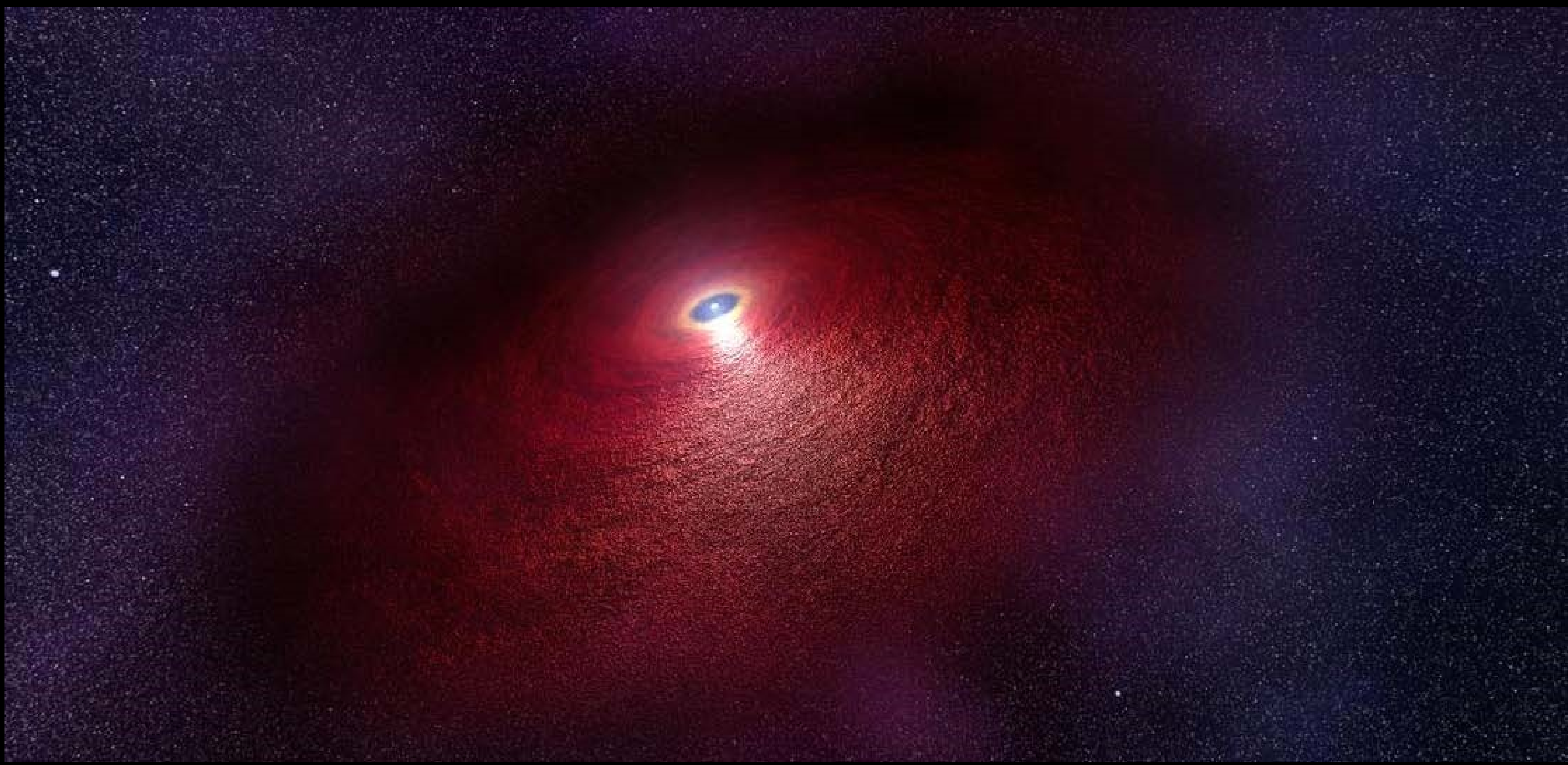
Detecting Never-Before-Seen Features around a Neutron Star

When a massive star explodes as a supernova, the star's leftover core collapses. If the core is between about one and three times the mass of the Sun, the process results in a newborn neutron star—one of the strangest objects in the universe. Neutron stars are the densest known objects that emit light. While powerful beams of light from a neutron star are normally seen in X-rays, gamma rays, and radio waves, *Hubble* used its near-infrared vision to view an unusual gush of infrared light coming from a region around a neutron star. Dubbed RX J0806.4-4123, this object is classified as a pulsar—a rapidly spinning neutron star.

The observation could indicate never-before-seen features around a neutron star. Astronomers suspect the infrared light might come from a dusty disk that is 18 billion miles across. Such a disk may have formed from material that coalesced around the neutron star following the supernova. Another explanation is that the neutron star may emit an energetic wind that slams into gas in interstellar space. Observations using future telescopes could reveal which is correct, opening a new window into understanding neutron stars.

"This particular neutron star belongs to a group of seven nearby X-ray pulsars—nicknamed 'the Magnificent Seven'—that are hotter than they ought to be."

Bettina Posselt, Pennsylvania State University

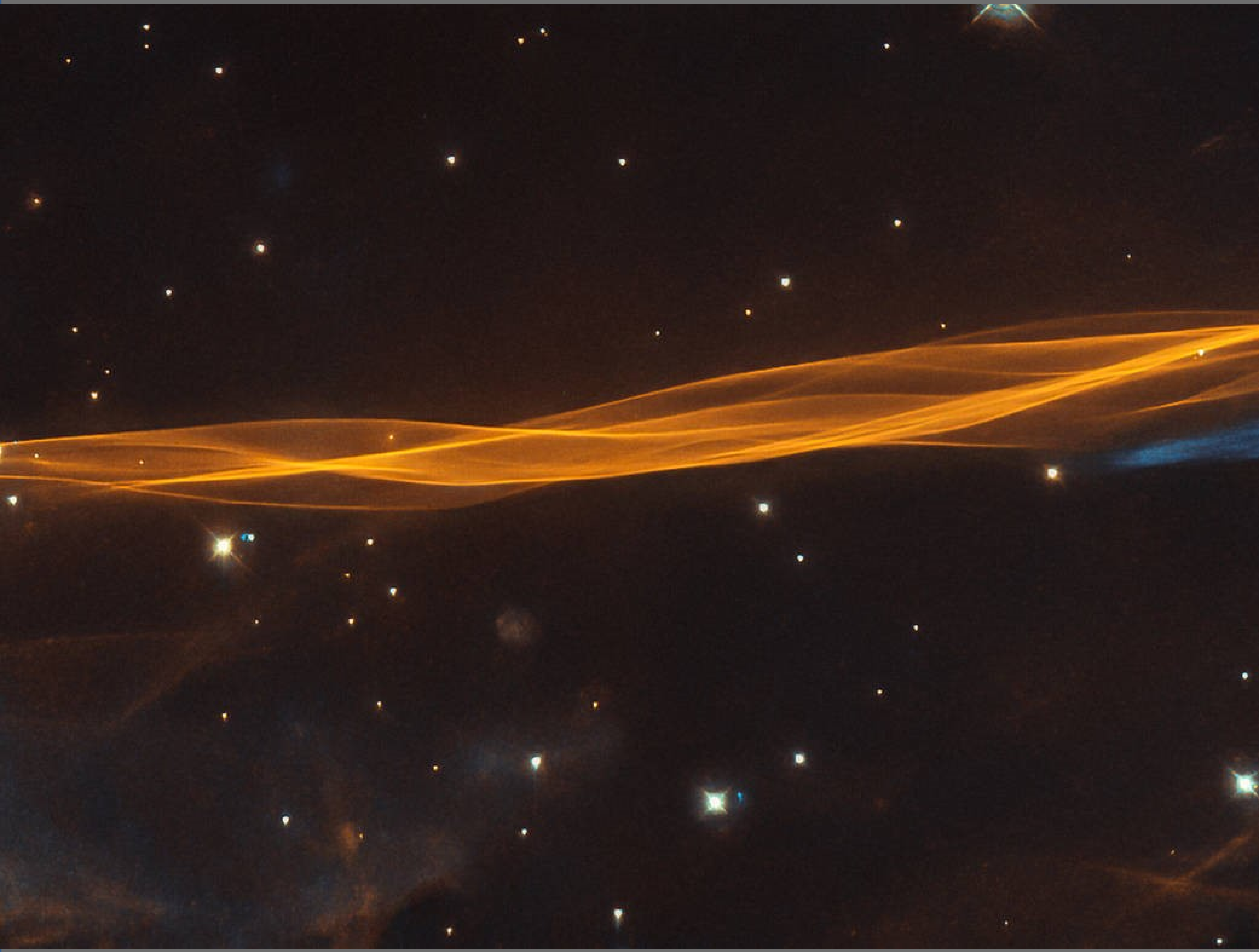


Hubble observed a relatively nearby neutron star, cataloged RX J0806.4-4123, and saw a strange gush of infrared light coming from the region around it. This illustration shows one possible explanation—a disk of warm dust surrounding the neutron star.

Credit: NASA, ESA, and N. Tr'Ehnl (Pennsylvania State University)

Learn more: https://hubblesite.org/contents/news-releases/2018/news-2018-43

Examining the Crime Scene around a Dead Star



What appears to be a flickering flame in this *Hubble* image is actually evidence of a star's death. A massive star exploded between 10,000 and 20,000 years ago. Stellar debris interacts with the interstellar medium to produce the tendril-like feature seen here, which is part of a larger structure known as the Cygnus supernova remnant.

Credit: ESA/*Hubble* & NASA, W. Blair; Acknowledgment: Leo Shatz

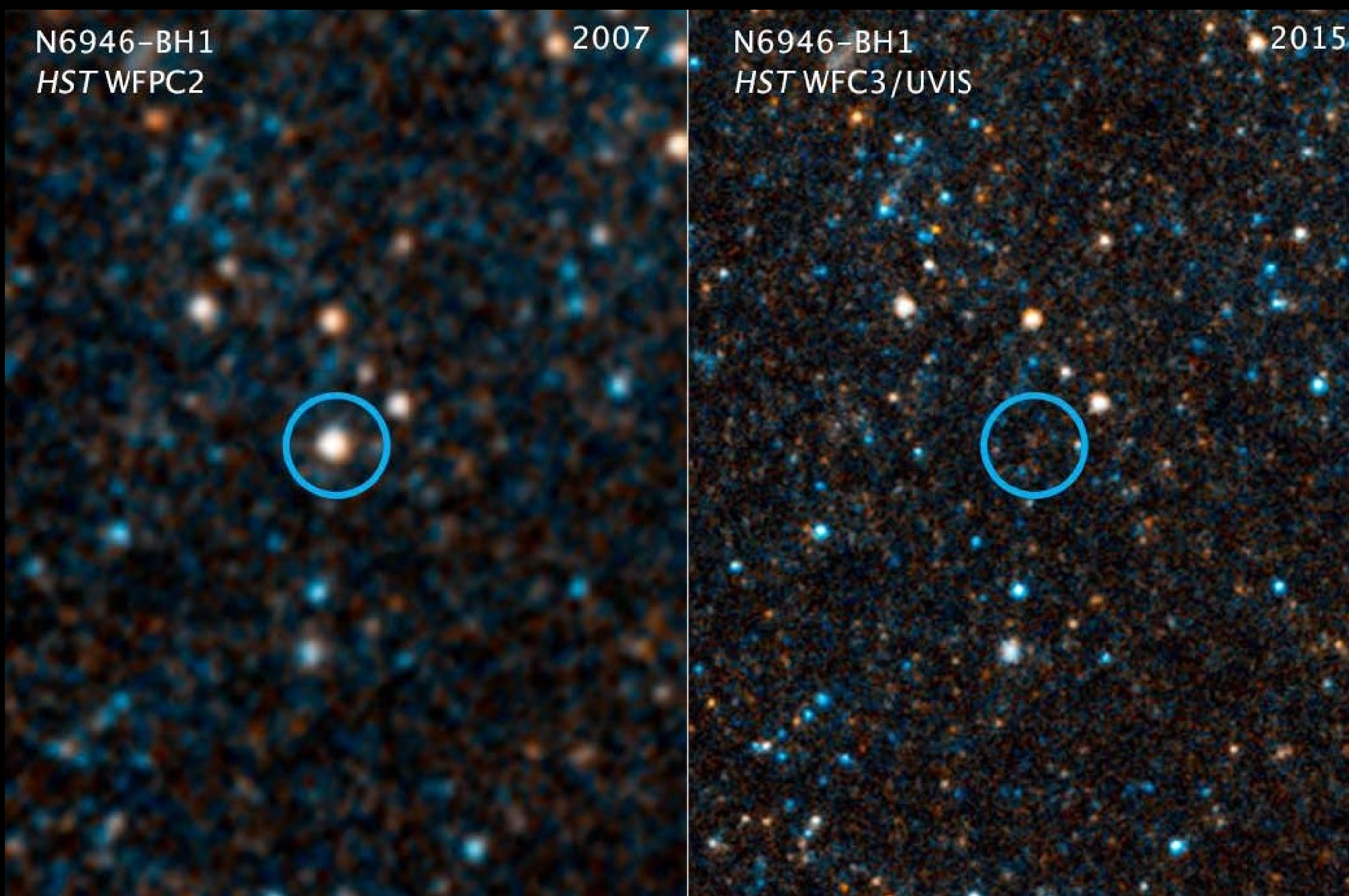
Discovering the Birth of a Black Hole from a Failed Supernova

Massive stars often end their lives in dramatic supernova explosions, but sometimes they can go out with a whimper instead of a bang. When they do, they may collapse under the crushing force of gravity and vanish out of sight, transforming directly into black holes. *Hubble* observed such a doomed star, called N6946-BH1, in a spiral galaxy 22 million light-years away. With a mass 25 times that of our Sun, astronomers expected that this star would explode in a very bright supernova.

Astronomers saw the star begin to brighten in 2009, but by 2015 it appeared to have winked out of existence. Based on observations by the Large Binocular Telescope in Arizona and the *Hubble* and *Spitzer* space telescopes, researchers carefully ruled out other possible explanations and concluded that the star must have become a black hole. Such may be the fate for as many as 10 to 30 percent of massive stars throughout the universe. The survey that revealed this discovery was prompted by the fact that we observe fewer supernovas than there should be if all massive star deaths include a supernova.

"If a star can fall short of a supernova and still make a black hole, that would help to explain why we don't see supernovas from the most massive stars."

Christopher Kochanek, Ohio State University



These two *Hubble* images, taken in 2007 with the Wide Field and Planetary Camera 2 (left) and in 2015 with the Wide Field Camera 3 (right), show the disappearance of a massive star 22 million light-years away named N6946-BH1. Astronomers think the star fizzled out and collapsed to form a black hole, skipping the usual supernova explosion.

Credit: NASA, ESA, and C. Kochanek (OSU)

Learn more: https://hubblesite.org/contents/news-releases/2017/news-2017-19

Watching an Exploding Star Fade into Oblivion

Hubble captured a star's disappearing act from 70 million light-years away, as part of a program to measure the universe's expansion rate. This video shows a time-lapse of the event, dubbed Supernova 2018gv, compressing nearly one year's worth of *Hubble* observations into a few seconds. The titanic explosion, which briefly outshined the entire host galaxy, originated from a white dwarf stealing material from its companion star. This pileup of gas eventually triggered a runaway nuclear explosion, before the star faded into obscurity.

Credit: NASA, ESA, M. Kornmesser and M. Zamani (ESA/*Hubble*), and A. Riess (STScI/JHU) and the SH0ES team

Providing a Holistic View of Stars Gone Haywire

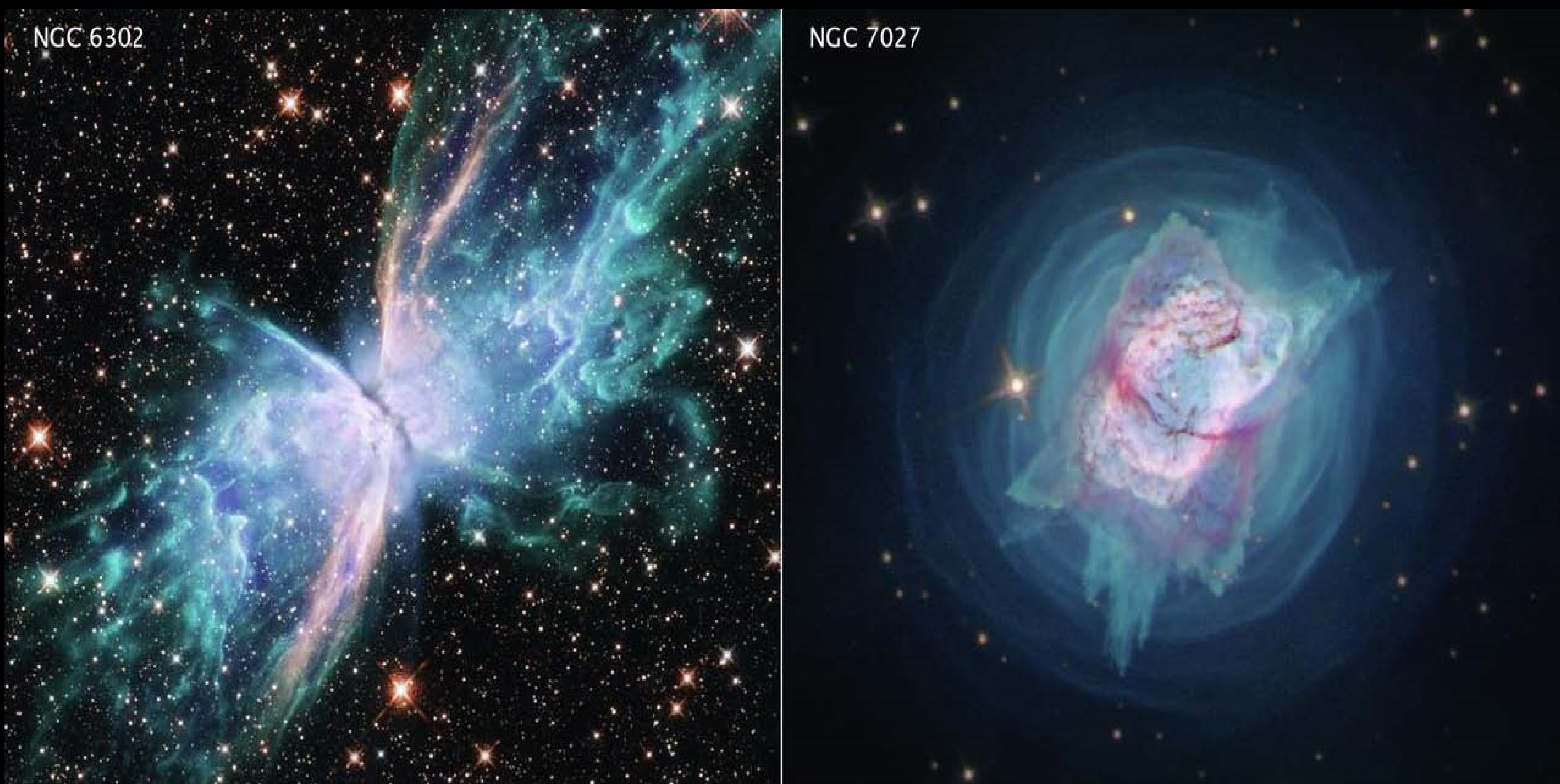
Planetary nebulas form over thousands of years when dying, average-sized stars shed their outer layers in shells and jets of hot gas. With the help of new *Hubble* images, researchers identified rapid changes in material blasting off stars at the centers of two such nebulas, causing them to reconsider what is happening at the nebulas' hearts.

In the case of NGC 6302, known as the Butterfly Nebula, two S-shaped streams indicate that two stars are interacting at the center of the nebula. In NGC 7027, a cloverleaf pattern, with bullets of material shooting out in specific directions, may also point to the interactions between two central stars. Both nebulas are splitting themselves apart on extremely short timescales, allowing researchers to measure changes in their structures over only a few decades.

This is the first time the nebulas have been studied from near-ultraviolet to near-infrared light, a complex, multi-wavelength view only possible with *Hubble*.

"These new multi-wavelength *Hubble* observations provide the most comprehensive view to date of both of these spectacular nebulas."

Joel Kastner, Rochester Institute of Technology



These new *Hubble* images are helping researchers explore the way planetary nebulas evolve. *Hubble*'s comprehensive, multi-wavelength view of the Butterfly Nebula (NGC 6302) revealed a pattern of iron emission, visible in near-infrared light (and colored pink here), which traces an S-shape from the lower left to the upper right of the image. This emission likely marks the central star system's most recent ejections of gas, which are moving much faster than the previously expelled material. *Hubble*'s image of NGC 7027 allowed astronomers to identify the nebula's central star in near-ultraviolet light. The observations will reveal how hot the star is and how much obscuring dust surrounds it.

Credit: NASA, ESA, and J. Kastner (RIT)

Learn more: https://hubblesite.org/contents/news-releases/2020/news-2020-31

Tracking Down the Source of Betelgeuse's Mysterious Dimming

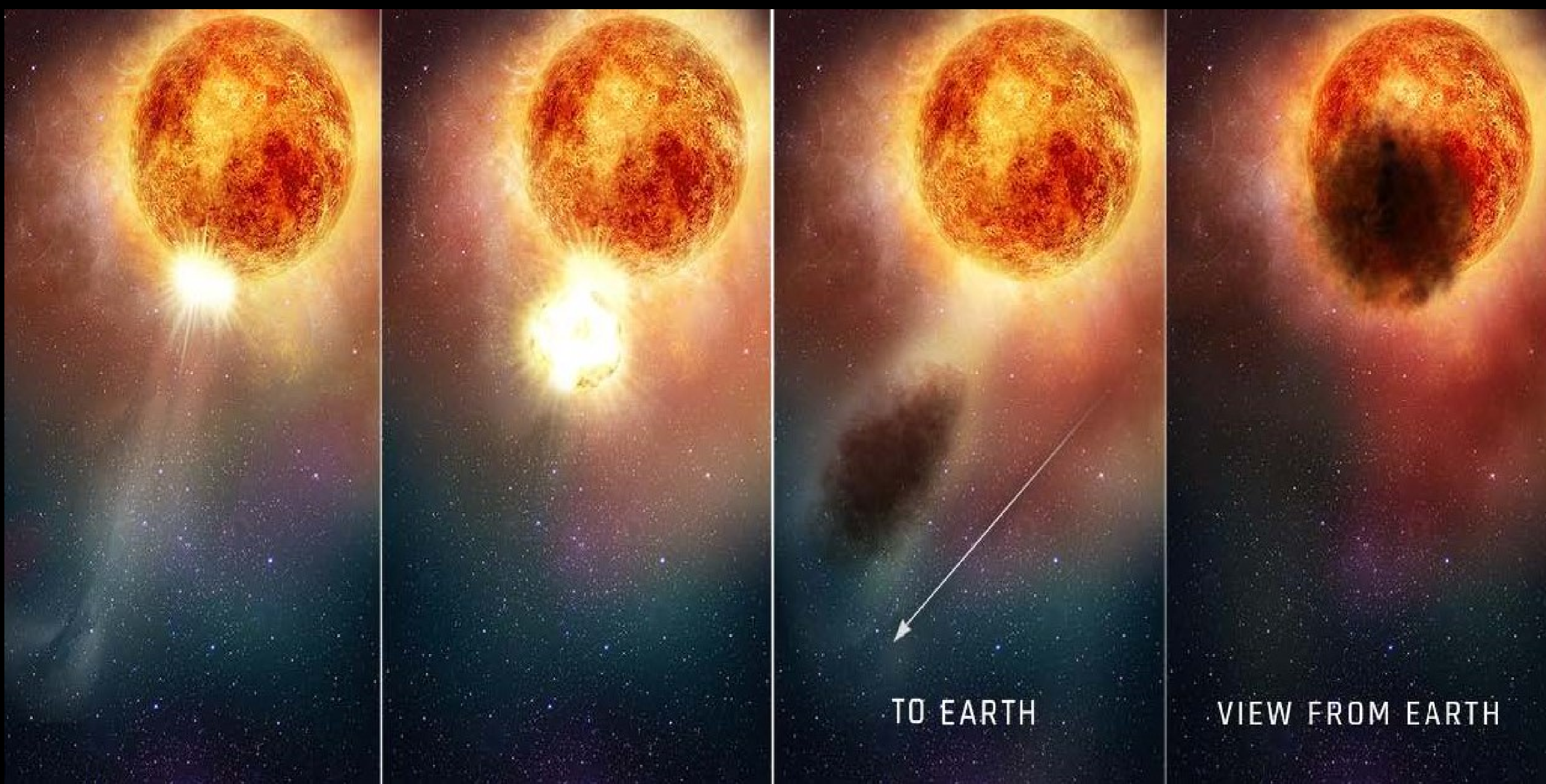
The aging, fiery-red supergiant star Betelgeuse, located only about 700 light-years away from Earth, is one of the brightest stars in the night sky. But Betelgeuse periodically swells and contracts, causing the star to visibly and routinely brighten and dim in the sky. However, in October 2019, the star dimmed dramatically and continued to become even fainter, instead of brightening again as expected. By mid-February 2020, the monster star had lost more than two-thirds of its brilliance.

The star’s sudden, dramatic dimming mystified astronomers, but ultraviolet observations from *Hubble* provide important clues about the possible cause. *Hubble* captured signs of dense, heated material moving through the star's atmosphere in September, October, and November 2019. Then, in December, several ground-based telescopes observed the star decreasing in brightness in its southern hemisphere. *Hubble*’s ultraviolet observations suggest that the dimming was probably caused by an immense amount of superhot material ejected into space. The material cooled and formed a dust cloud that blocked the starlight coming from about a quarter of Betelgeuse's surface.

The giant star is destined to end its life in a supernova blast. Some astronomers think the sudden dimming may be a pre-supernova event.

"Only *Hubble* gives us this evidence of what led up to the dimming."

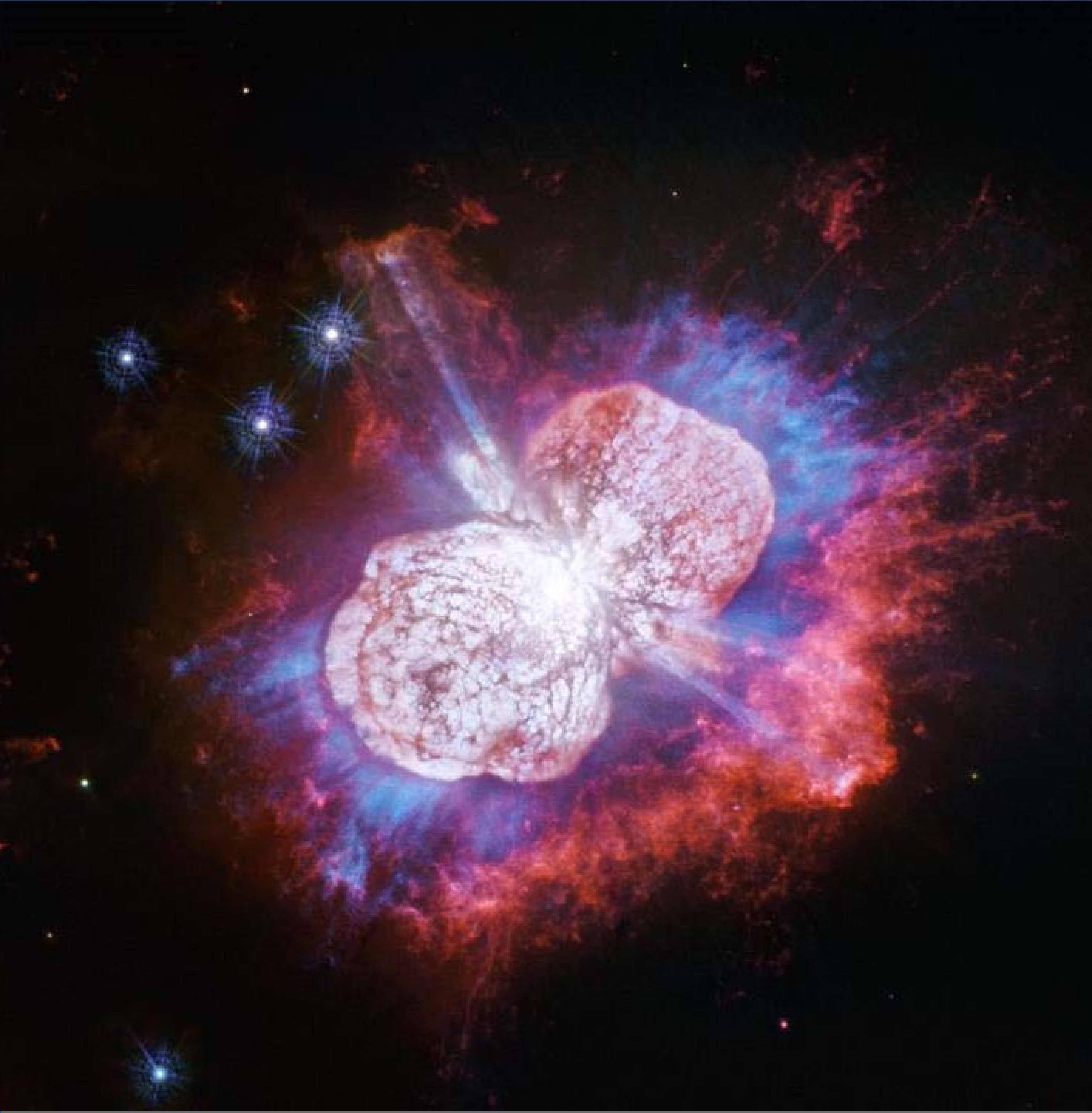
Andrea Dupree, Center for Astrophysics | Harvard & Smithsonian



This illustration shows a possible explanation for Betelgeuse’s dramatic dimming in late 2019. In the first two panels, a bright, hot blob of plasma is ejected from the star’s surface. In the third panel, the expelled gas rapidly expands outward and cools to form an enormous cloud of obscuring dust. The final panel reveals the huge dust cloud blocking the light (as seen from Earth) from a quarter of the star’s surface.

Credit: NASA, ESA, and E. Wheatley (STScI)

Learn more: https://hubblesite.org/contents/news-releases/2020/news-2020-44



The volatile star system Eta Carinae is thought to be on the brink of death. Eruptions from Eta Carinae have formed the glowing clouds of material featured in this *Hubble* image, which combines ultraviolet and visible light. *Hubble*'s ultraviolet observations revealed a previously hidden magnesium structure, shown here in blue, surrounding the stars. It resides in the space between the system's dusty bipolar bubbles and an envelope of nitrogen-rich filaments, shown in red.

Credit: NASA, ESA, N. Smith (University of Arizona), and J. Morse (BoldlyGo Institute)

CHAPTER 3: Star Clusters

Hubble has spotted countless stars roaming the galaxy alone or in pairs, but sometimes huge groups of stars are born in one giant litter. These groups, called star clusters, are held together by gravity. They come in two varieties: open and globular clusters.

Open star clusters are loosely bound, irregularly shaped groupings of up to several thousand relatively young stars. *Hubble* has found open clusters to be excellent astronomical laboratories. The stars may have different masses, but all are at about the same distance, move in the same general direction, and may have approximately the same age and chemical composition because they formed together in a massive cloud of gas and dust. By studying stars in open clusters, *Hubble* offers insight into stellar evolution and how the chemical makeup of stars varies from one to another.

Since they are only loosely held together, open clusters gradually disperse into space, pulled apart by the gravitational tugs of other passing clusters and clouds of gas. Most open clusters dissolve within a few hundred million years, whereas the more tightly bound globular clusters can exist for billions of years.

Globular star clusters are densely packed, spherical crowds of hundreds of thousands of stars. There are about 150 globular clusters embedded in the Milky Way's halo, which surrounds the entire galaxy like a giant, diffuse shell. *Hubble* used globular clusters to weigh the galaxy, and determine how much mass is locked up in dark matter. Globular clusters are also interesting because they contain some of the most ancient members of the galaxy. However, *Hubble* has revealed that at least some of the Milky Way's globular clusters may not have originated in our galaxy at all.

A star cluster sparkles in the center of this *Hubble* image, taken to commemorate *Hubble*'s 25th year in orbit. Dubbed Westerlund 2, the cluster was imaged in visible and near-infrared light, while the surrounding region was captured in visible light.

Credit: NASA, ESA, the *Hubble* Heritage Team (STScI/AURA), A. Nota (ESA/STScI), and the Westerlund 2 Science Team

The myriad stars in this *Hubble* image are members of the globular star cluster Messier 79, located 41,000 light-years from Earth. Our galaxy may have stolen this cluster, which contains about 150,000 stars, from another nearby galaxy in the not-too-distant past.

Credit: NASA and ESA; Acknowledgment: S. Djorgovski (Caltech) and F. Ferraro (University of Bologna)

Measuring the Distance to an Ancient Globular Star Cluster

Determining the distance to faraway cosmic objects is notoriously difficult. However, using *Hubble*, astronomers have now obtained precise measurements of the distances to some of the oldest objects in our universe—globular clusters.

The new estimates rely on the same sort of trigonometry that surveyors use on Earth, except that the angles measured in *Hubble*'s camera are far smaller. Nearby stars appear to shift slightly if viewed when Earth is at different points in its orbit. Astronomers used *Hubble* to measure the apparent shift of stars in NGC 6397, one of the closest globular clusters to Earth, very precisely. Using this measurement and the rules of trigonometry, the team calculated that the cluster is 7,800 light-years away.

The team also found the cluster's age by determining how intrinsically bright its stars are, since brighter stars exhaust their fuel more rapidly than fainter ones. With an age of 13.4 billion years, the cluster formed not long after the Big Bang. The measurement provides an independent estimate for the age of the universe and will also help astronomers improve models of stellar evolution.

"Globular clusters are so old that if their ages and distances deduced from models are off by a little bit, they seem to be older than the universe."

Tom Brown, Space Telescope Science Institute

This ancient stellar jewelry box—a globular cluster called NGC 6397—glitters with the light of hundreds of thousands of stars. Astronomers used *Hubble* to gauge the distance to this brilliant group of stars, providing the first precise measurement ever made to a globular cluster. At 7,800 light-years away, NGC 6397 is one of the closest globular clusters to Earth.

Credit: NASA, ESA, and T. Brown and S. Casertano (STScI); Acknowledgment: NASA, ESA, and J. Anderson (STScI)

Learn more: https://hubblesite.org/contents/news-releases/2018/news-2018-24

A star cluster sparkles in the lower right of this *Hubble* image. Known as R136, this cluster contains hundreds of young, blue stars, including some of the most massive stars detected in the universe so far. Astronomers using *Hubble* were able to conduct a detailed imaging and spectroscopic study of the central and most dense region of this cluster. Here they found nine stars with masses greater than 100 times the mass of the Sun.

Credit: NASA, ESA, and P. Crowther (University of Sheffield)

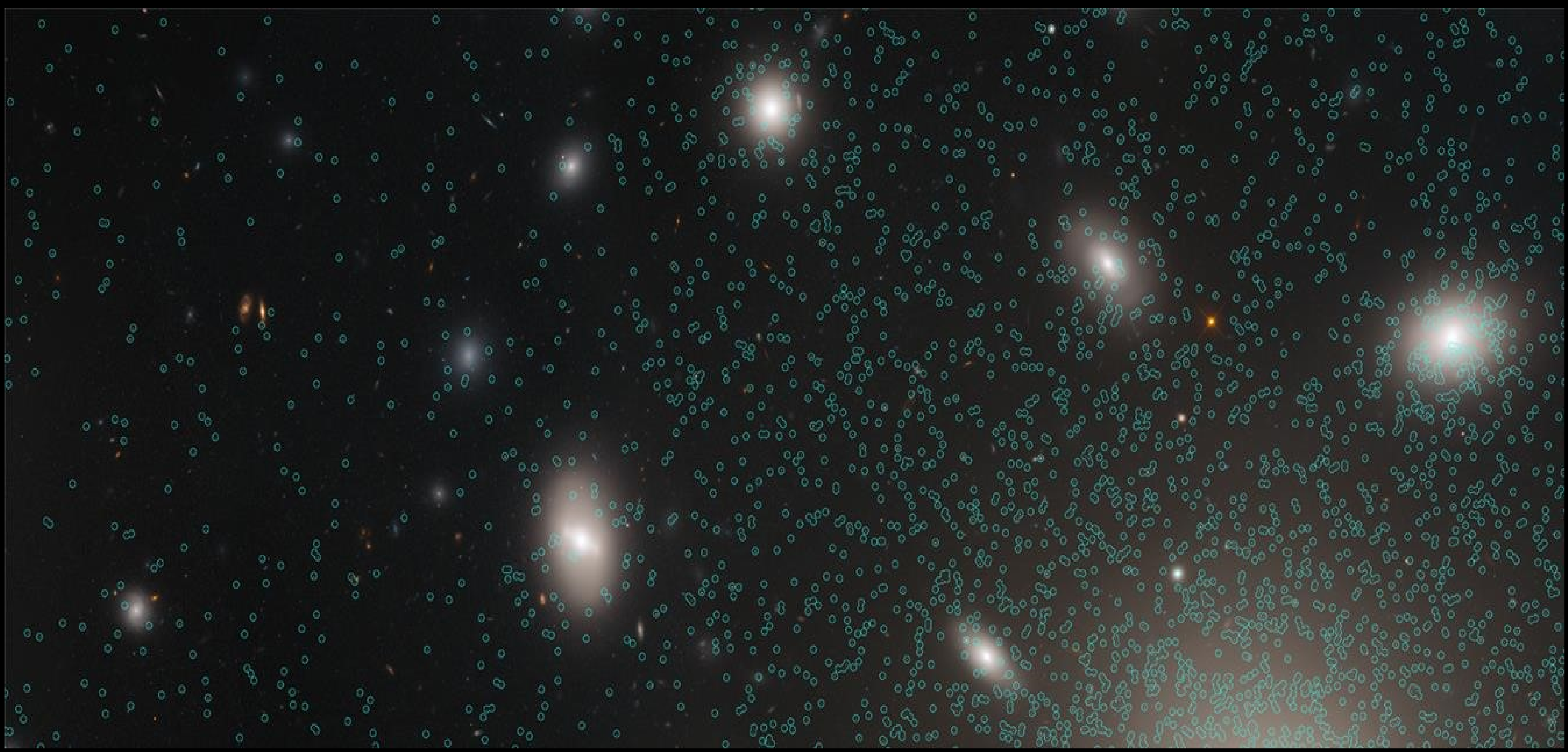
Unveiling Thousands of Globular Star Clusters

Studying globular star clusters enables astronomers to explore new realms of physics. *Hubble* peered across 300 million light-years to conduct a comprehensive census of globular clusters in the Coma cluster—a group of over a thousand galaxies packed relatively close together. The survey yielded 22,426 globular clusters scattered throughout the galaxies. The star clusters likely broke away from their home galaxies due to interactions with other galaxies in the traffic-jammed Coma cluster. They trace the gravitational field in the cluster, which in turn traces the distribution of the cluster's dark matter.

Since globular clusters are much smaller and more abundant than entire galaxies, they provide a more detailed way to study how the fabric of space is distorted by the Coma cluster's gravity. *Hubble* revealed that some globular clusters line up along bridge-like patterns. This is telltale evidence for interactions between galaxies where they gravitationally tug on each other like pulling taffy.

"The unique mosaic of deep *Hubble* images allowed us to construct the largest map of globular clusters in the Coma galaxy cluster ever made."

Alexander Gagliano, Virginia Tech University



Hubble mined the Coma cluster of galaxies in search of globular star clusters. The search revealed 22,426 globular clusters (circled in green), which astronomers are studying to help map the distribution of normal matter and dark matter throughout the Coma galaxy cluster.

Credit: NASA, ESA, STScI, J. Mack (STScI), and J. Madrid (Australian Telescope National Facility)

Learn more: https://hubblesite.org/contents/news-releases/2018/news-2018-44

Weighing Our Milky Way Galaxy

Our Milky Way galaxy contains an estimated 200 billion stars, but these stars account for only a small amount of the galaxy's matter. In the 1970s, American astronomer Vera Rubin discovered that stars toward the edge of the galaxy move too fast to be held in by the gravity from the galaxy's visible matter. This discovery added evidence supporting the theorized existence of a substance called dark matter. Dark matter doesn't emit any radiation, but its gravitational influence holds galaxies and galaxy clusters together. Scientists believe the Milky Way is surrounded by vast quantities of dark matter, but they have been unsure precisely how much.

Astronomers used *Hubble* and the European Space Agency's Gaia satellite to study the motions of globular star clusters that orbit our galaxy like bees around a hive. The faster the clusters move under the galaxy's gravitational influence, the more massive the galaxy must be. The researchers concluded that our galaxy weighs 1.5 trillion solar masses, with most of it locked up in dark matter. This measurement of the galaxy's mass allows astronomers to better understand how the myriad galaxies throughout the universe form and evolve.

"Globular star clusters are some of the best tracers astronomers have to measure the mass of the vast envelope of dark matter surrounding our galaxy."

Tony Sohn, Space Telescope Science Institute

This illustration shows the fundamental architecture of our Milky Way galaxy: a spiral disk, central bulge, and diffuse halo of stars and globular clusters. The Milky Way is also surrounded by invisible dark matter, which accounts for the vast majority of the galaxy's total mass.

Credit: NASA, ESA, and A. Feild (STScI)

Learn more: https://hubblesite.org/contents/news-releases/2019/news-2019-16

https://hubblesite.org/contents/media/images/2016/11/3717-Image.html

Hubble peered deep into the heart of our galaxy to reveal a rich tapestry of more than half a million stars. Except for a few blue foreground stars, the stars are part of a star cluster that surrounds the galaxy's central supermassive black hole. Known as the Milky Way's nuclear star cluster, it is the densest and most massive cluster in our galaxy.

Credit: NASA, ESA, and the *Hubble* Heritage Team (STScI/AURA); Acknowledgment: T. Do and A. Ghez (UCLA), and V. Bajaj (STScI)

Tracing the Evolution of Star Clusters

The Large Magellanic Cloud is a dwarf galaxy that orbits our Milky Way galaxy. Located about 160,000 light-years away, it is home to numerous star clusters of different ages. Astronomers noticed something puzzling about the galaxy's star clusters, though. While its young clusters all have small and tightly packed cores, the cores of its old clusters are both big and small. This led astronomers to think that clusters in the Large Magellanic Cloud formed with their stars crowded close together, only to have their stars spread apart, to varying degrees, over time.

However, observations using *Hubble* have revealed that the opposite is true—old clusters were born bigger, but became more compact over time. A team of scientists selected five old clusters, all about the same age, and used *Hubble* to study the distribution of blue straggler stars in each. Blue stragglers are bright blue stars with high masses. An earlier *Hubble* study revealed that gravitational interactions cause heavy stars like these to migrate toward the center of a star cluster over time. The more migration that has occurred in a star cluster, the greater the cluster's "dynamical age." The new *Hubble* study revealed that an old cluster's core size is related to its dynamical age, or how much its blue straggler stars have migrated. This was the first time that the effect of dynamical aging had ever been measured in clusters of the Large Magellanic Cloud.

"The star clusters are in different physical shape despite the fact that they were born at the same cosmic time."

Francesco Ferraro, University of Bologna

Hubble observed star clusters like this one, called NGC 1466, on the outskirts of the Large Magellanic Cloud—one of our closest galactic neighbors. Astronomers used the observations to study how different structures of star clusters are linked to different stages of evolution.

Credit: ESA and NASA

Learn more: https://hubblesite.org/contents/news-releases/2019/news-2019-42

CHAPTER 4: Stars as Cosmic Tools

People have marveled at the beauty of the stars for thousands of years. However, a true understanding of their nature remained elusive until relatively recently. As astronomers learned more about stars, they realized they could use the stars to discover more about the universe at large.

In the early 1900s, American astronomer Henrietta Swan Leavitt began cataloging the brightness of stars. For a special type of star that changes brightness, called a Cepheid variable, she discovered a relationship between a star's luminosity (average intrinsic brightness) and its period (the amount of time it takes to brighten, dim, and brighten again). That relationship allowed astronomers to measure the distance to remote galaxies, by comparing how bright their Cepheids appeared to the stars' actual luminosities. Another American astronomer, Edwin Hubble, later used these distances gauged by Cepheid variables to help determine that the universe is not static, as most people believed, but expanding. The telescope named after Hubble has extended these observations by helping to prove that the universe's expansion is accelerating. Ongoing studies may reveal clues to the nature of the cause of the acceleration, which has been dubbed "dark energy."

Hubble continues to transform our understanding of the universe in many ways by peering at stars scattered across space and time. Stars hold clues to galaxy formation and evolution, offering glimpses of the underlying physics of the cosmos. A dramatic tale of galactic cannibalism has emerged from *Hubble*'s observations of stars at the center of our galaxy. *Hubble*'s star studies have also confirmed the source of gravitational waves, which had never been done before. By exploring stars near and far, *Hubble* has even provided a way to trace many aspects of the evolution of the universe. Studying stars has revealed much about the past and present, and *Hubble*'s future observations may offer hints to the ultimate fate of the universe.

The spiral galaxy NGC 3021, which sparkles in the upper right corner of this *Hubble* image, contains Cepheid variable stars. Cepheids help astronomers determine cosmic distances because there is a relationship between their luminosity and period—the time it takes for them to brighten, dim, and brighten again.

Credit: NASA & ESA; Acknowledgment: A. Riess (STScI)

New stars are bursting into life in spiral galaxy NGC 3627, also known as Messier 66. *Hubble* studied NGC 3627 and 49 other galaxies as part of the Legacy ExtraGalactic UV Survey (LEGUS), the sharpest, most comprehensive ultraviolet-light survey of star-forming galaxies in the nearby universe. By learning more about how stars form, astronomers gain insight into the way galaxies evolve.

Credit: NASA, ESA, and the LEGUS team

Pinpointing the Source of Gravitational Waves

In 2017, the National Science Foundation's Laser Interferometer Gravitational-Wave Observatory (LIGO) detected gravitational waves—disturbances in space-time, the fabric of the universe—rippling across the cosmos. Since the gravitational waves were accompanied by light, astronomers were able to locate the source of the gravitational waves—something that had never been done before. The waves were produced when a pair of neutron stars collided in a galaxy 130 million light-years away. NASA's *Fermi Gamma-ray Space Telescope* detected the first pulse of light from the event as a powerful gamma-ray burst. *Hubble* performed follow-up observations, along with dozens of other observatories, to photograph the glow from the titanic collision.

Hubble also obtained an infrared spectrum to detect the chemical composition of the expanding debris. Revealing signs of exotic, radioactive elements, the spectrum perfectly matched what theoretical physicists predicted to see in the aftermath of a neutron star collision. Massive stars can create elements as heavy as iron within their cores, but heavier elements like gold and plutonium can only be produced by more powerful sources, such as neutron star collisions. The infrared spectrum obtained by *Hubble* confirmed the gravitational wave source beyond all reasonable doubt.

> "The detection of a gravitational wave source's light has revealed details of the event that cannot be determined from gravitational waves alone."
>
> **Paul Hertz, NASA Headquarters**

In 2017, *Hubble* located a brilliant flash called a kilonova that was produced by a pair of colliding neutron stars. The flare of light faded over the course of six days, shown in these observations taken on August 22, 26, and 28 (insets). This observation helped confirm the source of gravitational waves detected by LIGO.

Credit: NASA and ESA; Acknowledgment: A. Levan (U. Warwick), N. Tanvir (U. Leicester), and A. Fruchter and O. Fox (STScI)

Learn more: https://hubblesite.org/contents/news-releases/2017/news-2017-41

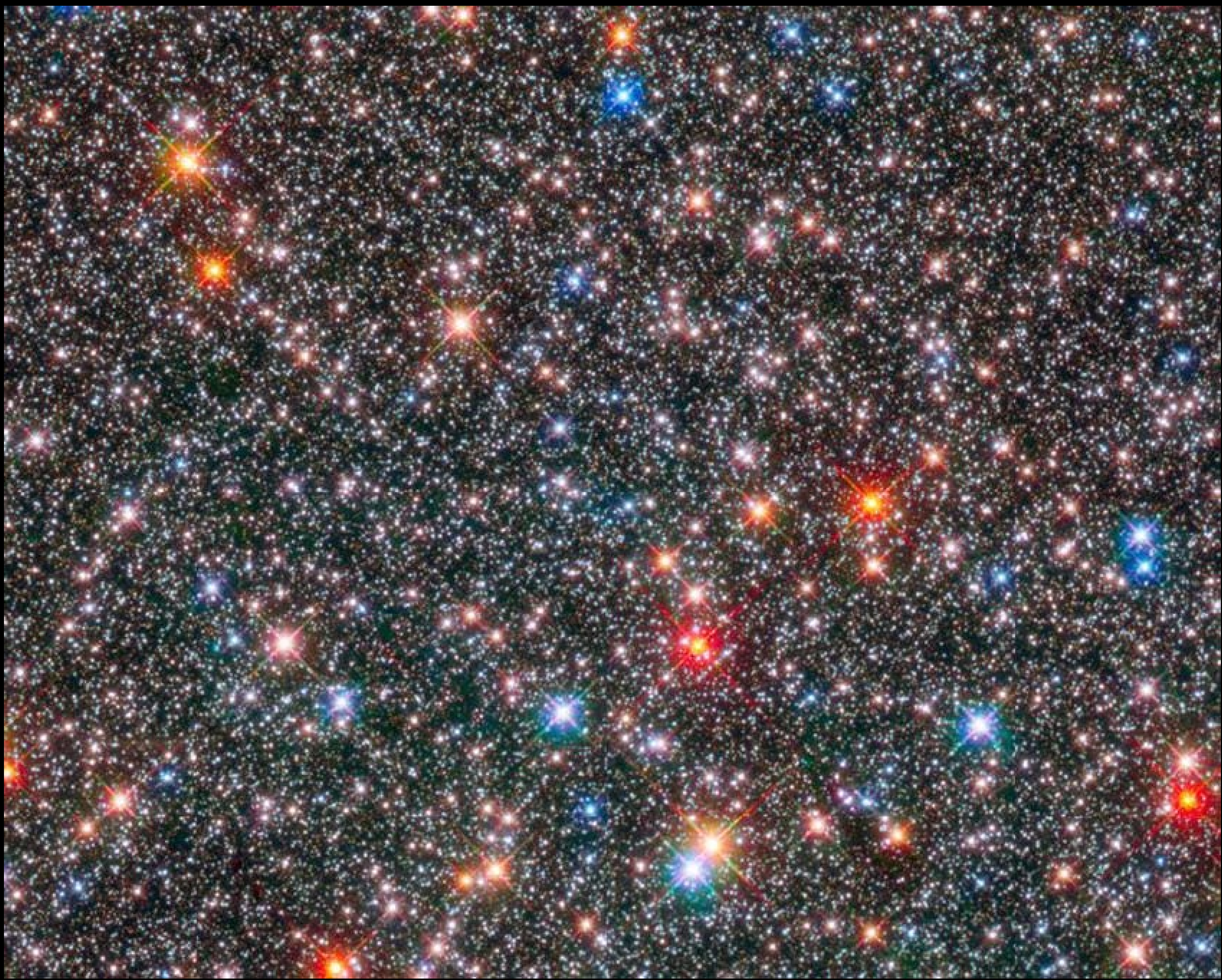
Revealing Clues about Our Galaxy's Formation

For many years, astronomers had a simple view of the central region of our Milky Way galaxy, known as the galactic bulge. They thought it was a relatively inactive place filled with ancient stars. However, a *Hubble* analysis of about 10,000 Sun-like stars in the heart of the galaxy revealed that the bulge is more dynamic and varied than astronomers thought.

The study, based on nine years' worth of archived *Hubble* data, may provide new insight into how the Milky Way evolved over billions of years. Instead of a relatively homogenous population of stars, astronomers found that stars of various ages whirl around the center of the galaxy at different speeds. The Milky Way may have cannibalized smaller galaxies, creating a population of faster-moving, younger stars. These stars mingle with a different population of older, slower-moving stars. Currently, only *Hubble* has sharp enough resolution to simultaneously measure the motions of thousands of Sun-like stars in the distant bulge.

"We are seeing thousands more stars than those spotted in earlier studies."

Anne Calamida, Space Telescope Science Institute



The glittering jewel box of stars in this *Hubble* image captures the heart of our Milky Way galaxy. Aging red giant stars and smaller white, Sun-like stars populate the crowded region of our galaxy's central hub, or bulge. Most of the bright blue stars in the image are probably recently formed stars located in the foreground, in the galaxy's disk.

Credit: NASA, ESA, and T. Brown (STScI); Acknowledgment: W. Clarkson (University of Michigan-Dearborn), and A. Calamida and K. Sahu (STScI)

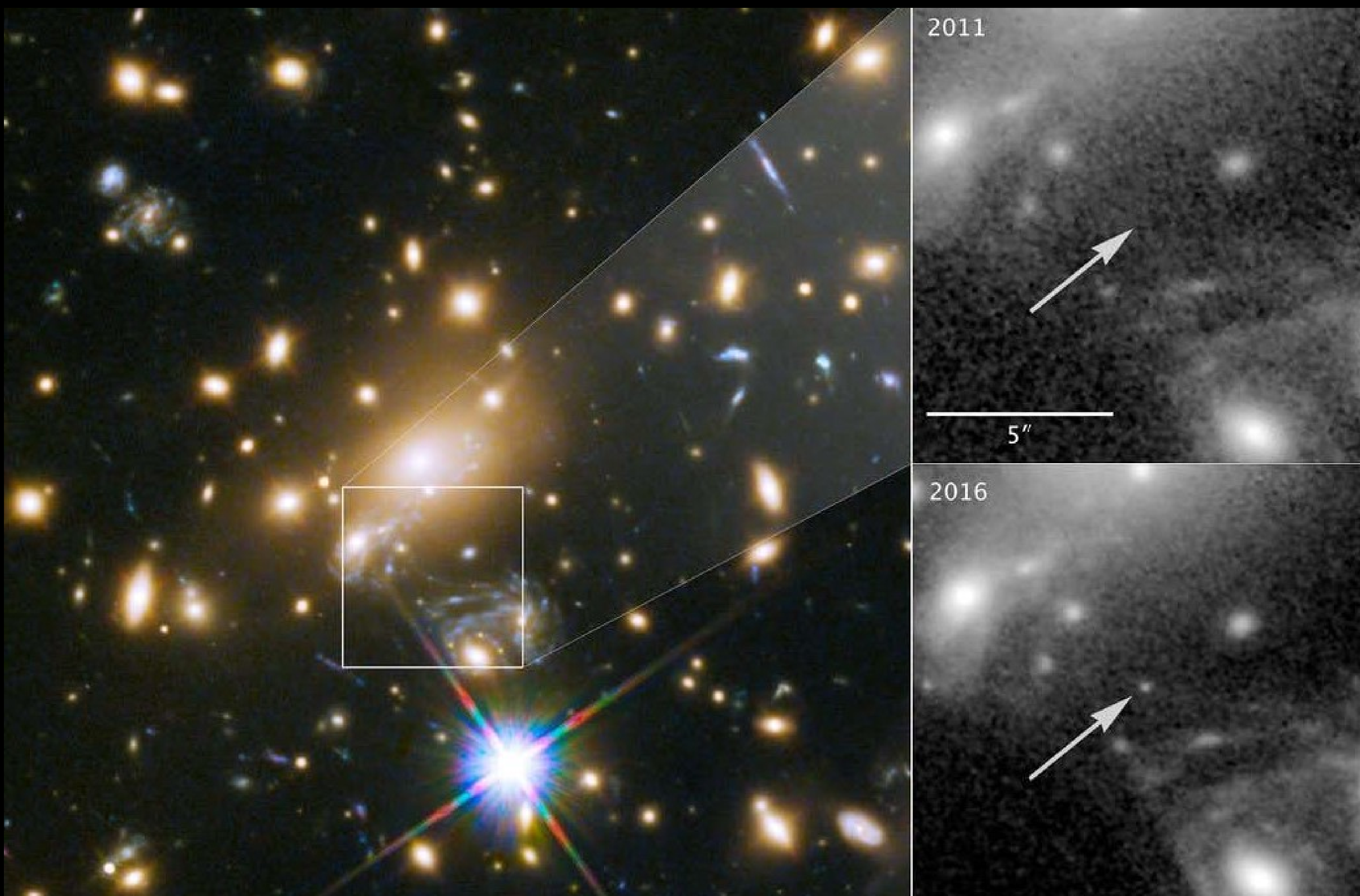
Learn more: https://hubblesite.org/contents/news-releases/2018/news-2018-01

Using a Cosmic Quirk to Expose the Farthest Star Ever Seen

Individually, extremely distant stars are often too faint for even *Hubble* to see, but a light-bending phenomenon can bring them into focus. Through a quirk of nature called gravitational lensing, *Hubble* peered more than halfway across the universe to view an enormous blue star. Formally called MACS J1149+2223 Lensed Star 1, the star is nicknamed Icarus after the character in Greek mythology. Gravity from a foreground galaxy cluster acted as a natural lens in space, bending and amplifying light from the more distant star. The gravitational lens was so strong that Icarus briefly skyrocketed to appear 2,000 times its true brightness, before returning to its original luster. The observation set a new record for the farthest individual star ever seen.

Icarus, harbored in a very distant spiral galaxy, is so far away that its light took 9 billion years to reach Earth. It appears to us as it did when the universe was about 30 percent of its current age. *Hubble*'s observation provides a rare, new way to study how stars evolve. Astronomers also used the observation to test a theory of dark matter and probe the composition of the foreground galaxy cluster.

> "This star is at least 100 times farther away than the next individual star we can study, except for supernova explosions."
>
> **Patrick Kelly, University of Minnesota, Twin Cities**



Hubble used a cosmic quirk to set a new record for the farthest individual star ever seen. The galaxy cluster shown at the left (MACS J1149+2223) sits between Earth and the star, which is nicknamed Icarus. Gravity from the cluster amplified light from the more distant star, which is nestled in a faraway spiral galaxy. Since it is 9 billion light-years away, Icarus would normally be much too faint for even *Hubble* to observe.

Credit: NASA, ESA, and P. Kelly (University of Minnesota)

Learn more: https://hubblesite.org/contents/news-releases/2018/news-2018-13

Painting a Picture of the Evolving Universe

Astronomers have assembled one of the most comprehensive portraits yet of the universe's evolutionary history, capturing star formation in thousands of galaxies. *Hubble* peered across the cosmos to track the birth of stars over the last 11 billion years, back to the busiest star-forming period in the universe. *Hubble*'s ultraviolet vision added to infrared and visible-light observations, taken by *Hubble* and other telescopes, to capture a sea of approximately 15,000 galaxies. The resulting image represents one of the largest panoramic views of the fire and fury of star birth in the distant universe.

About 12,000 of the 15,000 galaxies in the new mosaic are forming stars, and the galaxies are widely distributed in space and time. *Hubble*'s observation opens a new window on cosmic evolution because astronomers can study stellar birth rates at different eras of the universe. By comparing star formation in the distant and nearby universe, astronomers glean a better understanding of how nearby galaxies grew from small clumps of hot, young stars long ago. Ultraviolet light has been the missing piece to the cosmic puzzle, partly because Earth's atmosphere filters out most ultraviolet light. Above the atmosphere, *Hubble* provides some of the most sensitive ultraviolet observations possible.

"These new images from *Hubble* provide the missing link. They allow us to see galaxies in the exact same light across the expanding universe."

Pascal Oesch, University of Geneva

Of the roughly 15,000 galaxies captured in this image, which combines observations from *Hubble* taken in ultraviolet, visible, and infrared light, about 12,000 host regions of active star birth. Studying star formation at different cosmic eras provides a window into how the universe evolved to its present state.

Credit: NASA, ESA, P. Oesch (University of Geneva), and M. Montes (University of New South Wales)

Learn more: https://hubblesite.org/contents/news-releases/2018/news-2018-35

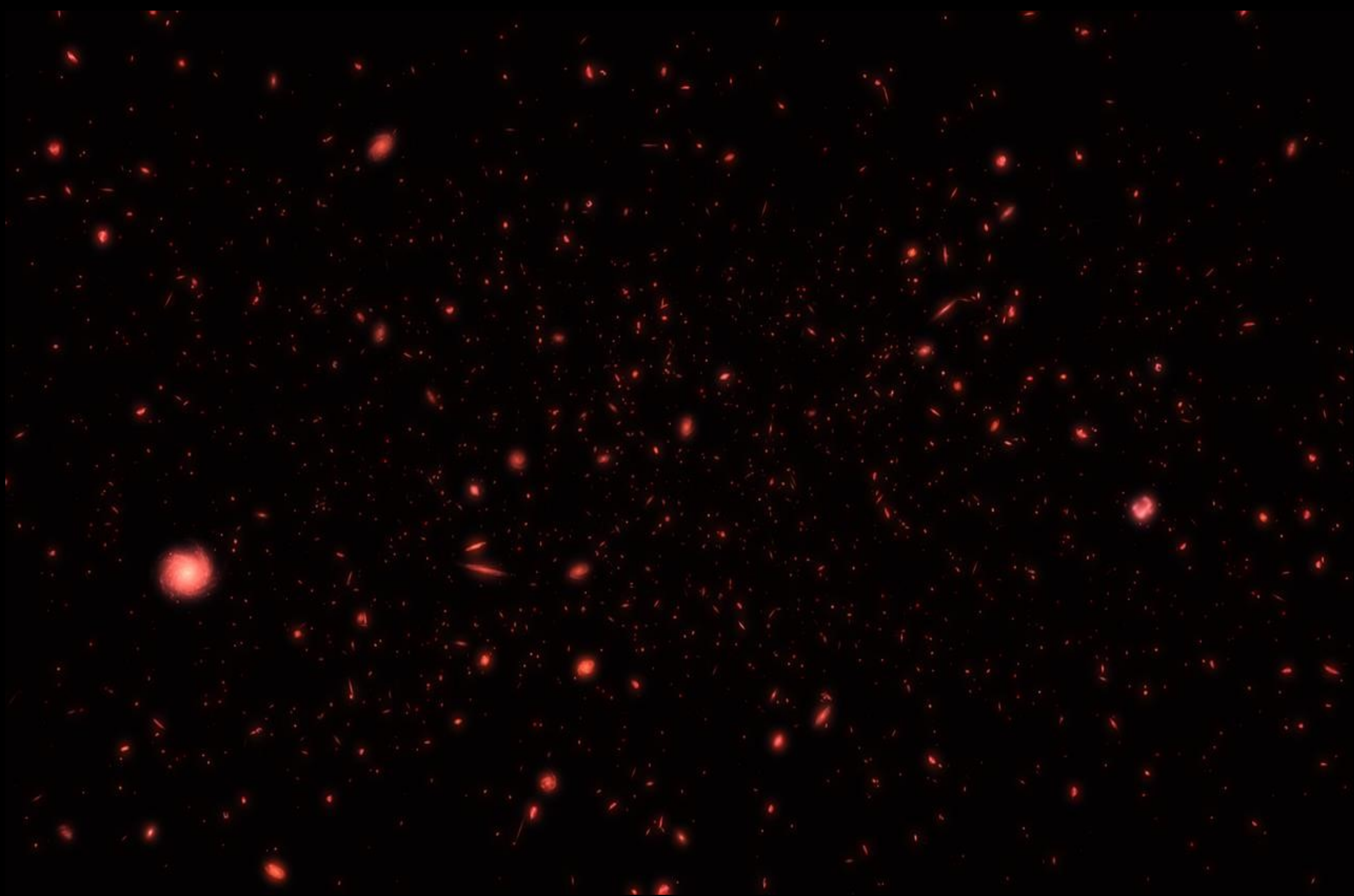
Making a Surprising Find in the Early Universe

A team of researchers used *Hubble*, *Spitzer*, and the Very Large Telescope to search for the first generation of stars that formed in the universe, known as Population III stars. These early stellar settlers were very different from modern-day stars, like our Sun, since they were solely made out of the few primordial elements forged in the seething crucible of the Big Bang. Thought to be much more massive and brighter than our Sun, Population III stars manufactured additional elements and seeded the universe with them, so successive generations of stars were composed of a larger variety of elements.

Astronomers have long wondered when these very first stars formed. In an attempt to find the answer, researchers harnessed the gravitational power of a massive galaxy cluster (MACS J0416) to peer back to when the universe was between 500 million and one billion years old, or about 3.5–7% of its current age. They relied on a phenomenon called gravitational lensing, which occurs when the gravity of a massive foreground object bends and amplifies light from more distant sources. The team unveiled far-flung galaxies that are 10 to 100 times fainter than any previously observed, however they found no evidence of Population III stars. These results are important because they show that stars and galaxies must have formed earlier than previously thought.

"These results have profound astrophysical consequences as they show that galaxies must have formed much earlier than we thought."

Rachana Bhatawdekar, European Space Agency



This illustration presents a conceptual view of the early universe, speckled with scarlet galaxies. Everything is tinted red because light shifts to longer (redder) wavelengths as it travels across vast astronomical distances, due to the expansion of space.

Credit: ESA, M. Kornmesser, and NASA

Learn more: https://hubblesite.org/contents/news-releases/2020/news-2020-34

Confirming a Discrepancy in the Universe's Expansion Rate

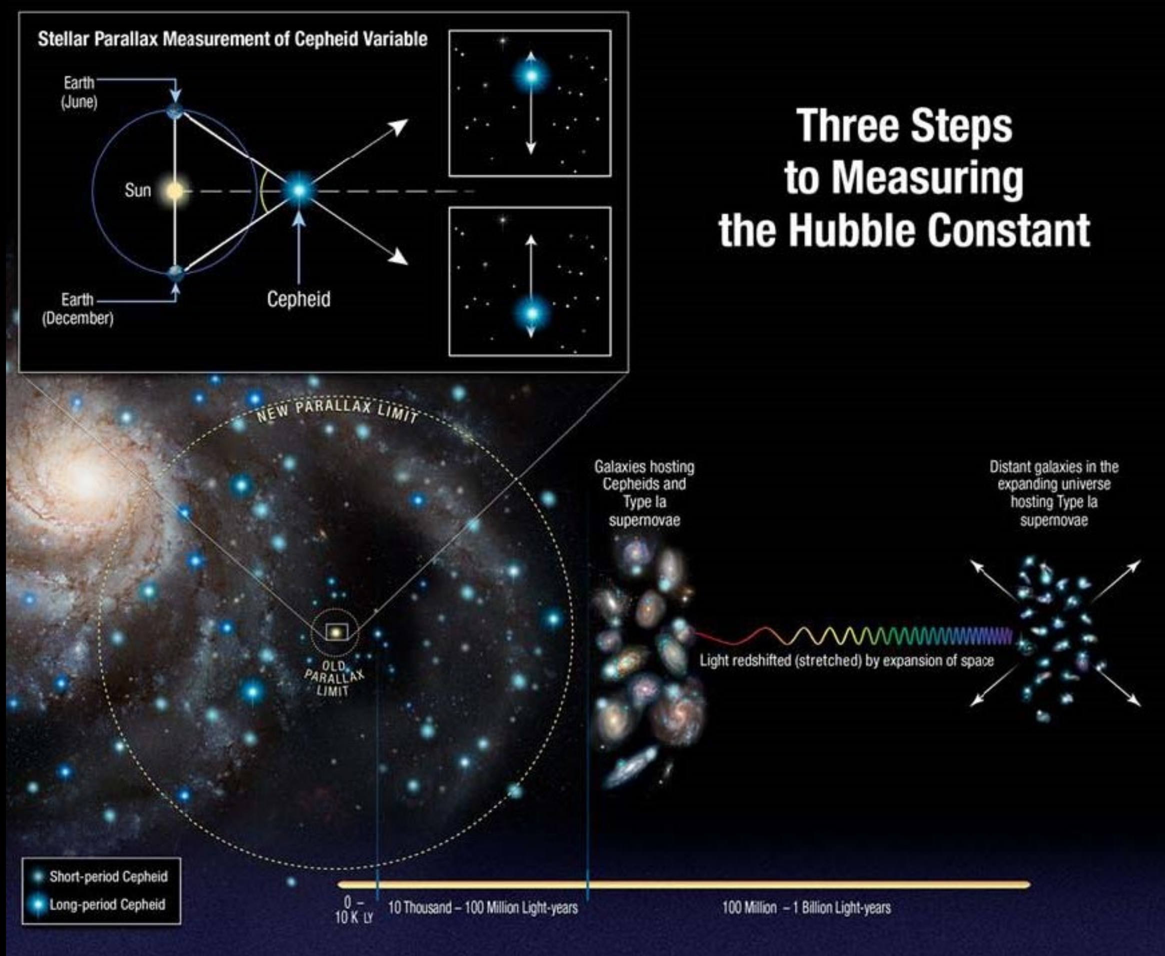
Astronomers using *Hubble* have made the most precise measurement to date of the universe's expansion rate. They did so by applying innovative technical methods to improve their distance measurements to Cepheid variable stars in our galaxy and a nearby galaxy called the Large Magellanic Cloud. The scientists then used these measurements to calibrate the distances to galaxies that host both Cepheids and Type Ia supernovas—bright explosions that can also be seen in even farther galaxies where individual Cepheids cannot be resolved. This allowed the team to calculate distances to hundreds of supernovas in far-flung galaxies with greater precision, and to compare the galaxies' distances to how fast they're moving away.

However, the results confirm a major discrepancy. *Hubble*'s measurements of the expansion rate of the modern universe do not match the rate predicted from observations of the early universe by the European

Space Agency's *Planck* spacecraft. According to the cosmological model based on *Planck* data from about 380,000 years after the Big Bang, the universe should be expanding at about 67 kilometers per second for every megaparsec (about 3.26 million light-years) of distance. However, *Hubble* measured a value of 74 kilometers per second per megaparsec, indicating that galaxies are moving apart faster than predicted. *Hubble*'s precise measurements suggest that there's only a 1 in 100,000 chance that the discrepancy in the predicted and measured expansion rate is a fluke. The discrepancy may mean that there is something unknown about the makeup of the universe. One explanation is that dark energy may not have a constant strength.

"The community is really grappling with understanding the meaning of this discrepancy."

Adam Reiss, Space Telescope Science Institute and Johns Hopkins University



This illustration shows one method used to refine the Hubble constant, which describes how fast the universe is currently expanding. The box at the upper left illustrates how astronomers used *Hubble* to measure the parallax of pulsating stars called Cepheid variables. Parallax measurements allow astronomers to measure distances from the apparent shift of an object's position due to a change in the observer's point of view. As depicted at the lower left, *Hubble* was able to expand its parallax measurements to Cepheids that are much farther away than any studied before. The lower right explains how Cepheids are used to calibrate the distance to supernovas and the galaxies that host them, providing more accurate distance measurements even farther into space.

Credit: NASA, ESA, A. Feild (STScI), and A. Riess (STScI/Johns Hopkins University)

Learn more: https://hubblesite.org/contents/news-releases/2018/news-2018-12

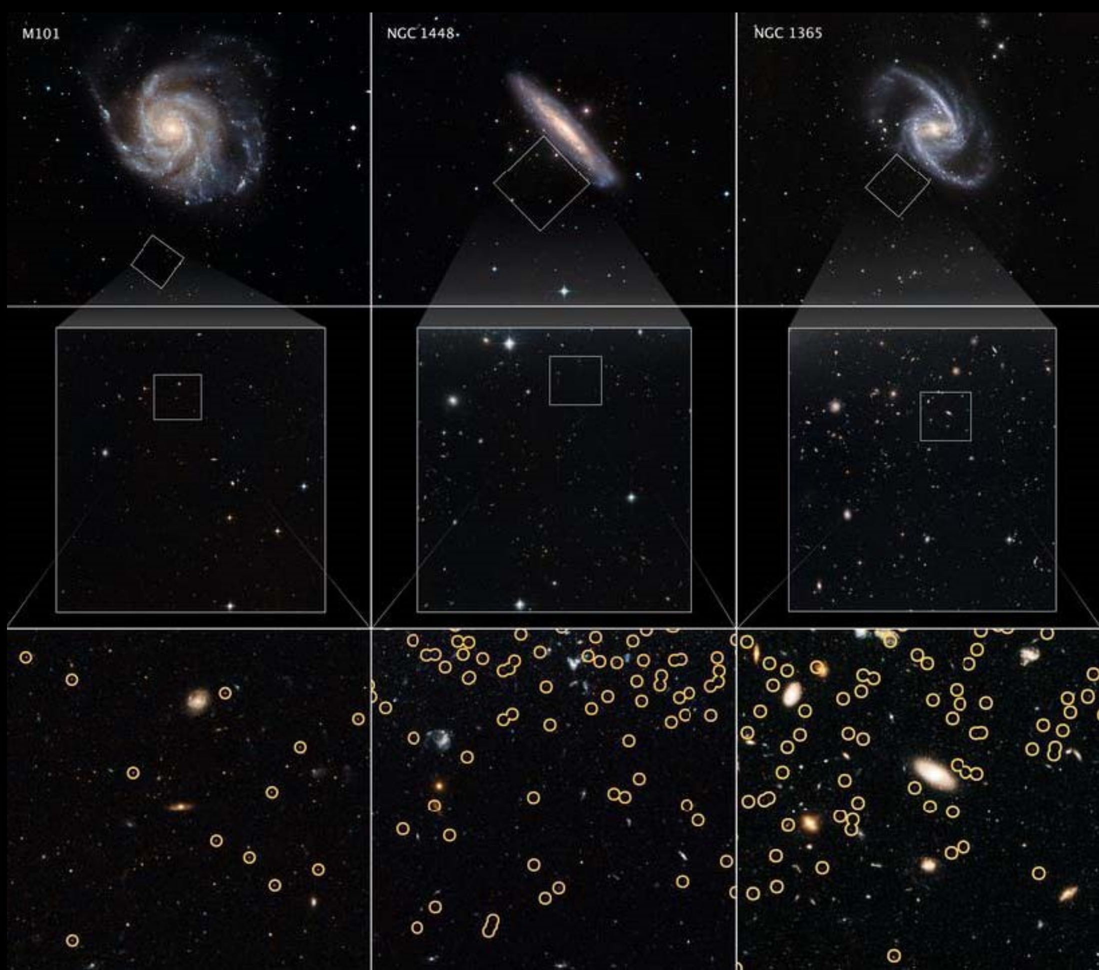
Deepening the Mystery of the Universe's Expansion Rate

After other studies revealed a nagging discrepancy between predicted and measured expansion rates of our universe, one team of astronomers hoped to resolve the mismatch by using a different method to determine how fast the universe is expanding. Instead of using Cepheid variable stars to measure distances to nearby galaxies, as other studies have, the new study relied on red giant stars. At a certain point in their lifetime, red giants undergo a catastrophic event called a helium flash, which always reaches the same peak brightness. Astronomers used *Hubble* to measure the apparent brightness of red giant stars at this stage in different galaxies and determine their distances. This offers an alternate way to calibrate the distance to Type Ia supernovas in even farther galaxies by studying galaxies that host both red giants in this stage and Type Ia supernovas. By comparing each galaxy's distance to how fast it appears to be moving away from us, the team calculated how fast the universe is expanding—70 kilometers per second per megaparsec (km/s/Mpc).

This result lies between Cepheid-based measurements of the modern universe's expansion rate (74 km/s/Mpc) and expansion rates predicted by observations of the early universe (67.4 km/s/Mpc). So it does not appear to strongly favor either, though it aligns more closely with the predictions. This underscores the discrepancy, hinting that perhaps there is something astronomers do not yet understand about the stars they are measuring, or the standard model of cosmology remains incomplete. Additional studies will be needed to help solve the mystery.

"The jury is still out on whether there is an immediate and compelling reason to believe that there is something fundamentally flawed in our current model of the universe."

Wendy Freedman, University of Chicago



The galaxies in the top row were selected to help measure the expansion rate of the universe. The boxes in the middle row zoom into the squares outlined in the top row, and the bottom row zooms in even tighter. Astronomers used *Hubble* to determine how far away the galaxies are by comparing the apparent brightness of some of their red giant stars (identified by yellow circles) with nearby red giants, whose distances were measured with other methods. Then they compared the galaxies' distances to how fast they appear to be moving away from Earth.

Credit: NASA, ESA, W. Freedman (University of Chicago), ESO, and the Digitized Sky Survey

Learn more: https://hubblesite.org/contents/news-releases/2019/news-2019-28

The star-studded galaxy in this *Hubble* image (NGC 1015) holds a key to one of the greatest ongoing mysteries in cosmology. With the help of the galaxy's Cepheid variable stars, astronomers fine-tuned measurements of the universe's expansion rate. Their results underscored the mismatch between values predicted from observations of the early universe and measurements of the modern universe, highlighting a major gap in our understanding of the cosmos.

Credit: NASA, ESA, A. Riess (STScI/JHU)

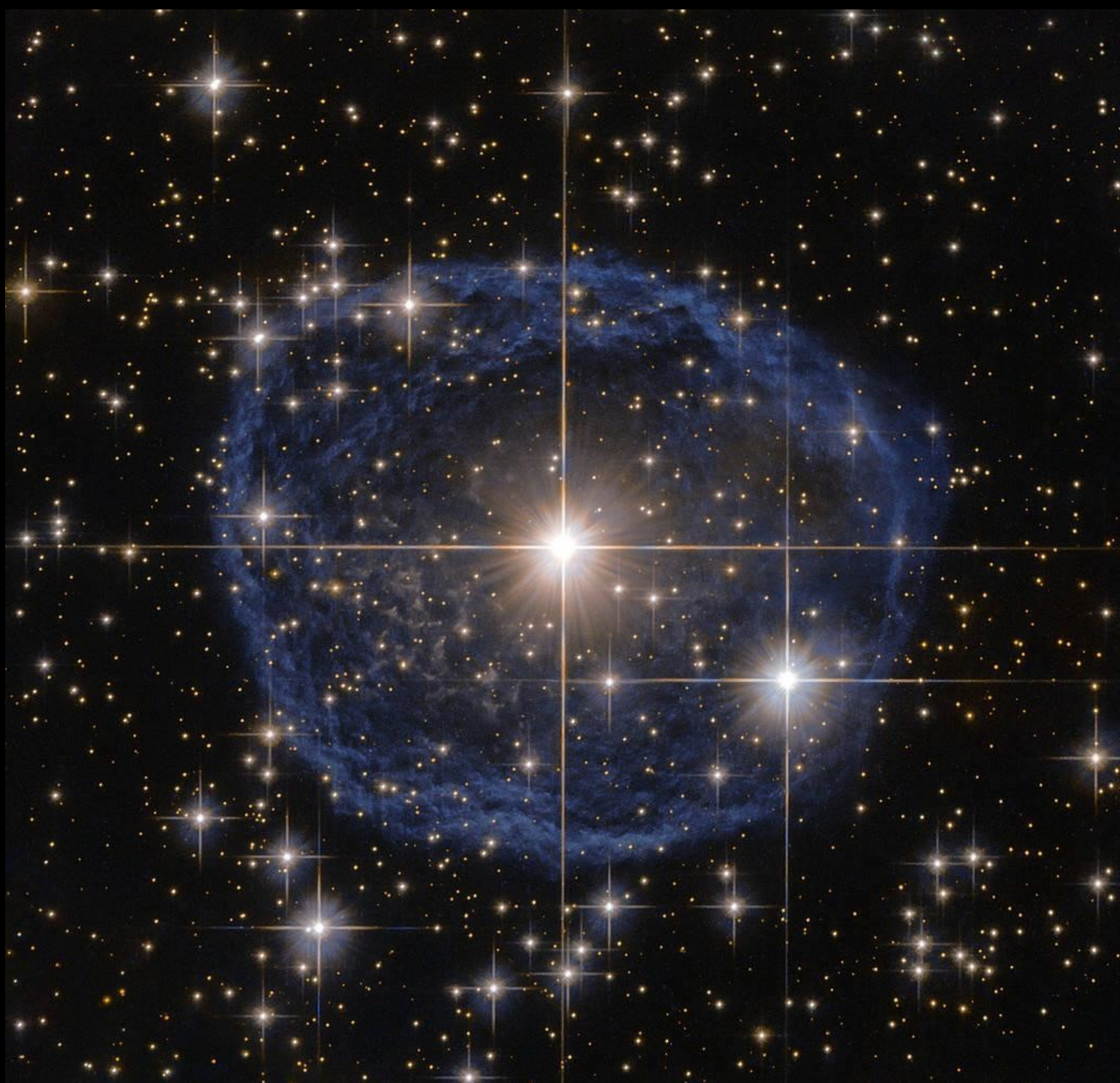
SUMMARY

Hubble has captured troves of peaceful celestial scenes in its gallery of star images. Like brilliant diamonds against the inky void of space, each twinkling star is a radiant cosmic wonder. Many stars grace the galaxy for billions and billions of years, leading tame and rather uneventful lives. *Hubble* has even spotted some that are nearly as old as the universe itself, providing a window to the distant past.

But *Hubble* has also shown that some seemingly peaceful stars are actually raging infernos that violently blast out gas and intense radiation. Studying them in multiple wavelengths of light has allowed scientists to explore many different stellar characteristics—some of which had never been seen before. Meanwhile, *Hubble* has seen signs of planets forming in the dusty debris whirling around young stars, and it has also glimpsed some massive stars that exploded and sent shrapnel out into space, sterilizing any nearby planets in the process.

Thanks to *Hubble*, scientists have been able to use star clusters to weigh our Milky Way galaxy and trace the distribution of dark matter. The myriad stars strewn across space and time exhibit a wide range of phenomena, and studying them continues to help us understand the universe and our place within it.

If it weren't for stars, none of us would be here to ponder the cosmos. In sharp contrast to our current star-filled universe, the earliest cosmic era contained no stars at all. Future telescopes, such as the *Nancy Grace Roman Space Telescope* and *James Webb Space Telescope*, will complement and extend *Hubble*'s star studies by exploring the epoch when the very first stars were born. *Hubble* will continue to advance our understanding of stars by scanning the skies for years to come, conducting exciting initiatives such as the UV Legacy Library of Young Stars as Essential Standards (**ULLYSES**) program. Through this effort, *Hubble* will observe hundreds of stars in ultraviolet light—something no other observatory is currently capable of doing. Many mysteries permeate the story of how our universe formed and evolved to its present state. Using *Hubble* and other telescopes to explore stars will help us solve them.



An eerie blue orb drifts through the galaxy about 30,000 light-years from Earth. This *Hubble* image shows a central star (WR 31a) lighting up a surrounding bubble of gas, which is made up of the star's ejected outer layers. The bubble is expanding at around 136,700 miles per hour.

Credit: ESA/*Hubble* & NASA; Acknowledgment: Judy Schmidt

MORE INFORMATION

For more information about the *Hubble Space Telescope* mission and its discoveries, visit NASA's *Hubble* website at nasa.gov/hubble. For additional details and resources, visit HubbleSite.org.

Follow *Hubble's* exploration of stars at the following social media sites.

Facebook

https://www.facebook.com/NASAHubble

Twitter

https://twitter.com/NASAHubble

Instagram

https://www.instagram.com/NASAHubble

YouTube

https://www.youtube.com/playlist?list=PL3E861DC9F9A8F2E9

Flickr

https://www.flickr.com/photos/nasahubble

Pinterest

https://www.pinterest.com/nasa/hubble-space-telescope/

The stars in this *Hubble* image are collectively known as Caldwell 58 (or NGC 2360)—an open cluster located roughly 3,700 light-years from Earth. Astronomers used *Hubble* to study white dwarfs in the cluster and better understand the age of our galaxy.

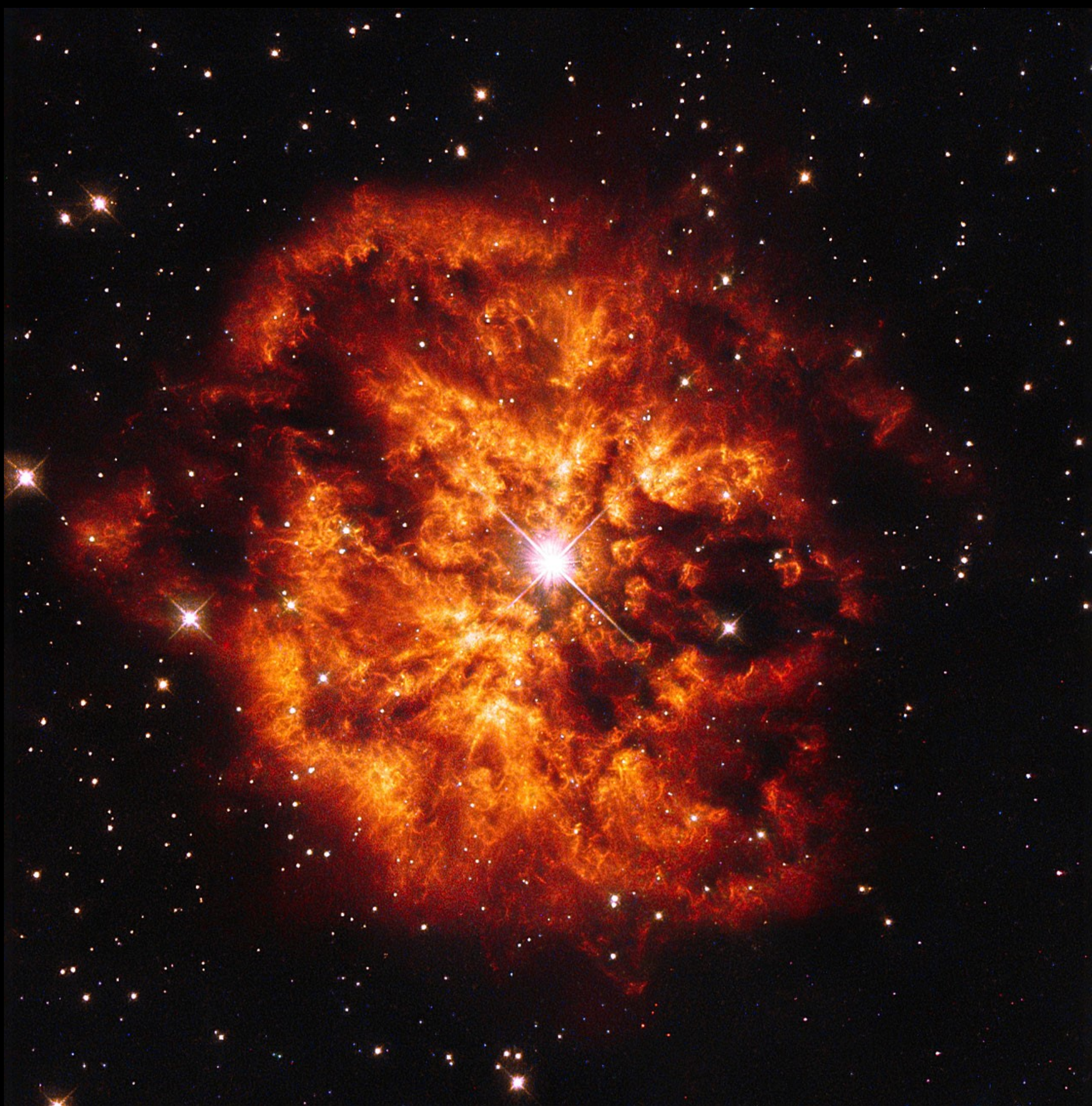
Credit: NASA, ESA, and T. von Hippel (Embry-Riddle Aeronautical University); Processing: Gladys Kober (NASA/Catholic University of America)

CREDITS

The *Hubble Space Telescope* is a cooperative project between the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA). The Space Telescope Science Institute (STScI), operated by the Association of Universities for Research in Astronomy (AURA), conducts the science operations for the *Hubble Space Telescope* under contract NAS5-26555.

Hubble Focus: The Lives of Stars was produced by NASA's Goddard Space Flight Center (GSFC). It was published in May 2021.

The production team for this book included Ashley Balzer (writer), Katrina Fajardo and Ed Henderson (designers), Ken Carpenter and Jennifer Wiseman (science advisors), Kevin Hartnett, James Jeletic, and Vanessa Thomas (editors) at GSFC.



The star WR 124 lights up a brilliant, tangerine-colored nebula in this *Hubble* image. WR 124 is ejecting gas outward at speeds over 90,000 miles per hour into the surrounding nebula.

Credit: ESA/*Hubble* & NASA; Acknowledgment: Judy Schmidt (geckzilla.com)