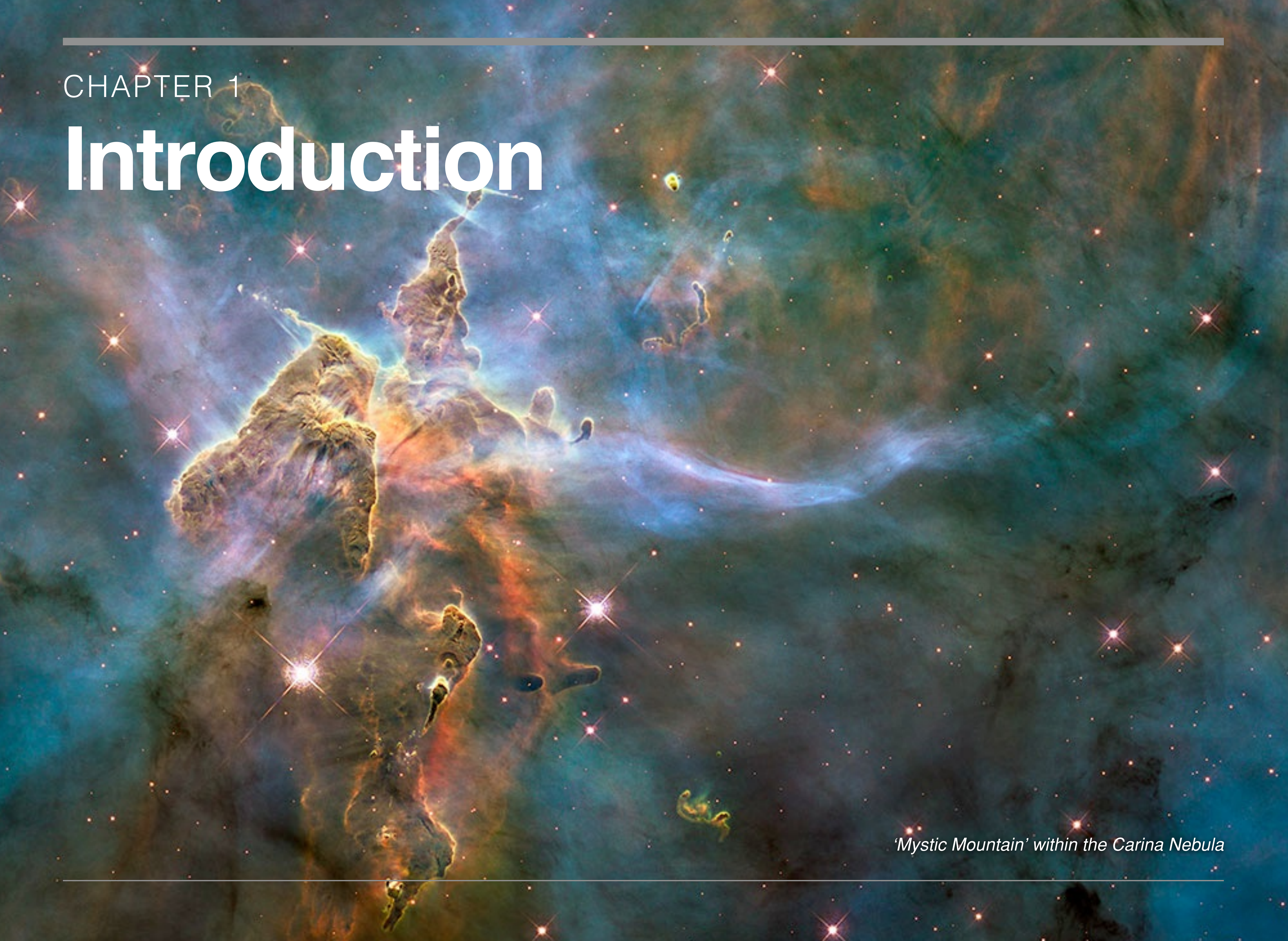
EDITION: 1.4

HubbleSite.org

Hubble Space Telescope Discoveries

CHAPTER 1

Introduction



‘Mystic Mountain’ within the Carina Nebula

For best viewing

Viewing in portrait orientation removes several layout features.

HubbleSite & WebbTelescope
Produced by the Space Telescope Science Institute

Version: 1.4

Release date: December, 2012

Look at the night sky, and you see primarily darkness. A vast multitude of glittering sparks drift over our heads, scattered across the sky. Our gaze registers their beauty but little else. Our vision cannot bring these dazzling pinpoints into focus, observe their true nature. To our eyes, they are mysteries.

Since the days of Galileo, humanity has sought to move beyond the limited vision of biology. Telescopes have brought the heavens to Earth, exposed the distant treasures of the universe, revealed countless galaxies cloaked within the apparent darkness. And perhaps no telescope has done so much to bring the wonder and reality of the universe home as the Hubble Space Telescope.

Launched in 1990, Hubble – a joint project of NASA and the European Space Agency – orbits Earth 353 miles (569 km) above the planet's surface. Its position allows it to circle free of Earth's atmosphere, which distorts and blocks light from the cosmos. This gives Hubble a pristine view typically unmatchable by ground-based telescopes. As the telescope whips around Earth once every 97 minutes, it collects light – much more light than our human eyes can hope to capture on their own. Light that reveals everything from the nature of storms on Jupiter to some of the most distant galaxies in the universe.

Where we see points of light, Hubble sees structure. Where we see a haze, Hubble sees detail. And where we see darkness, Hubble finds the dim glow of the early universe.

Hubble's explorations have helped answer some of the most compelling cosmic mysteries of our time – and uncovered a host of new questions, new mysteries awaiting the gaze of future telescopes to further push back the darkness.

Hubble Discoveries that Capture the Imagination

Everyone has had a moment of wonder looking up at the sky – seeing a shooting star, watching an eclipse of the Moon, observing the rare comet passing through the night.

Hubble's discoveries have made headlines and sometimes changed the face of astronomy – but what observations captured the imagination of the people who work directly with the telescope?

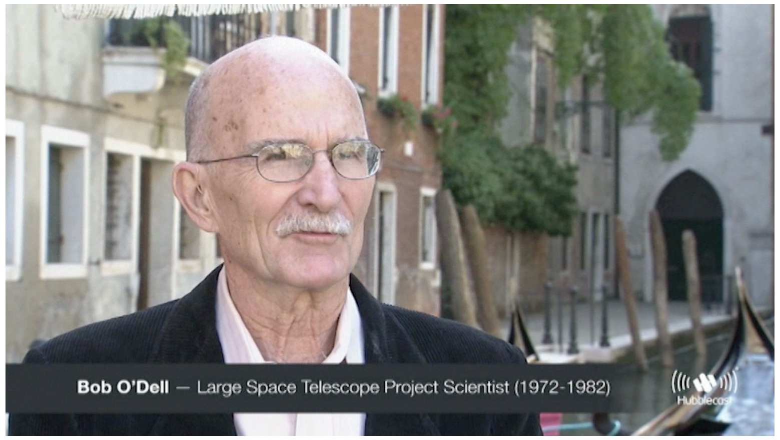
In these videos, leading scientists who have used the Hubble Space Telescope discuss their favorite discoveries, the ones that brought out their sense of wonder and their joy in astronomy.

Movie 1.1 Astronaut John Grunsfeld

Movie 1.2 Astronomer Laura Ferrarese

Movie 1.3 Astronomer Monica Tosi

Movie 1.4 Project Scientist Bob O'Dell

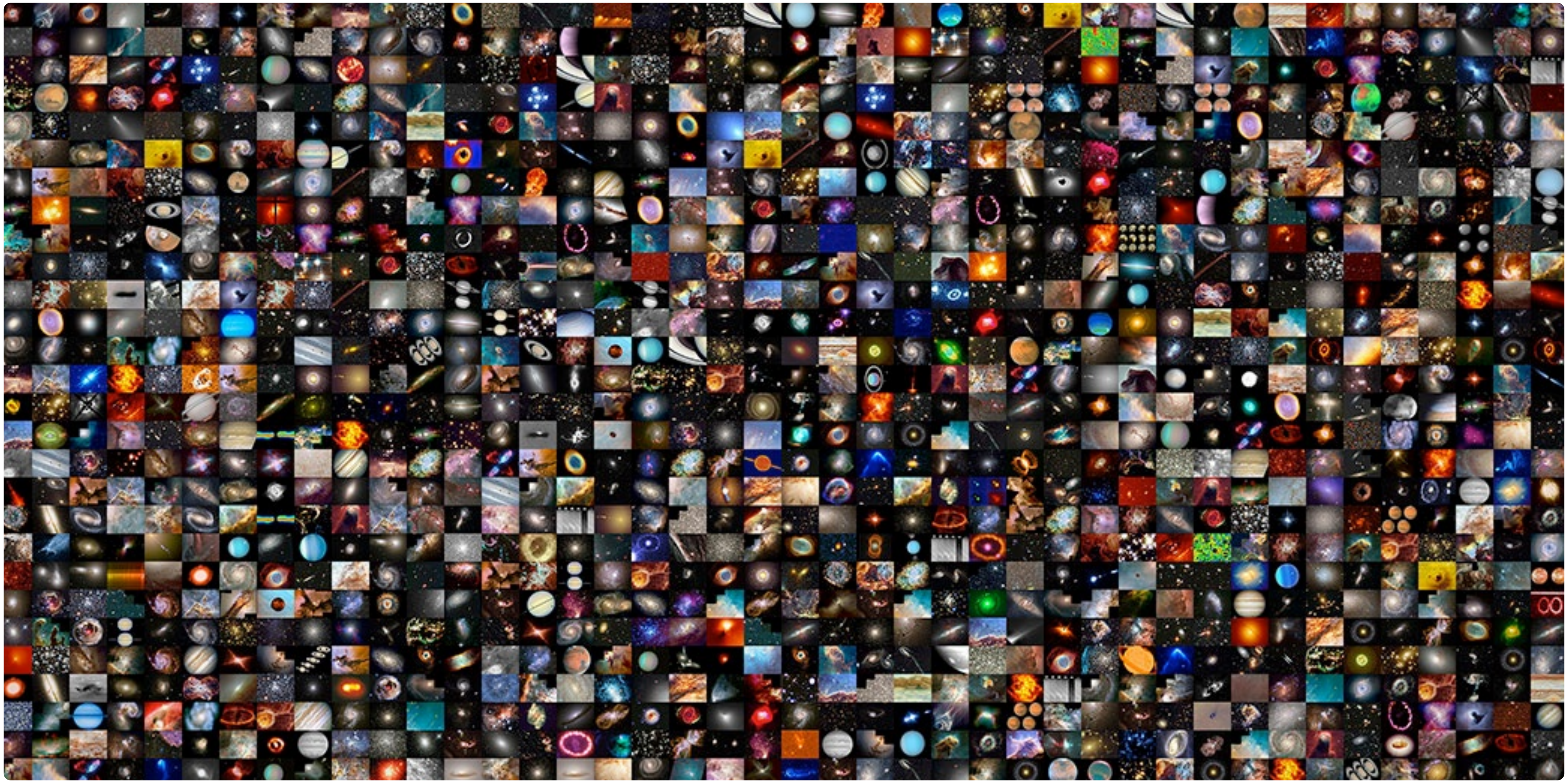


Movie 1.5 Senior Project Scientist Dave Leckrone

Movie 1.6 Professor Sandra Faber

SECTION 1

Gallery



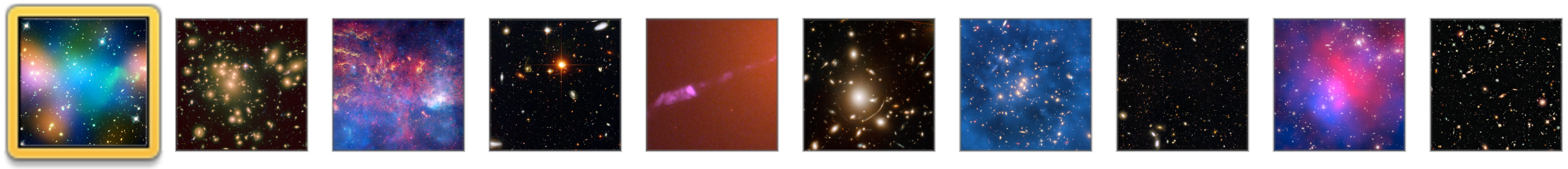
Explore the universe through Hubble's eye, and witness the most dangerous, spectacular and mysterious depths of the cosmos. Through the following collection of Hubble images – planets, nebulae, galaxies and cosmology – a sample of the vast universe lies before you in all its dazzling complexity. Capture the extraordinary ...

Gallery 1.1 Nebulae

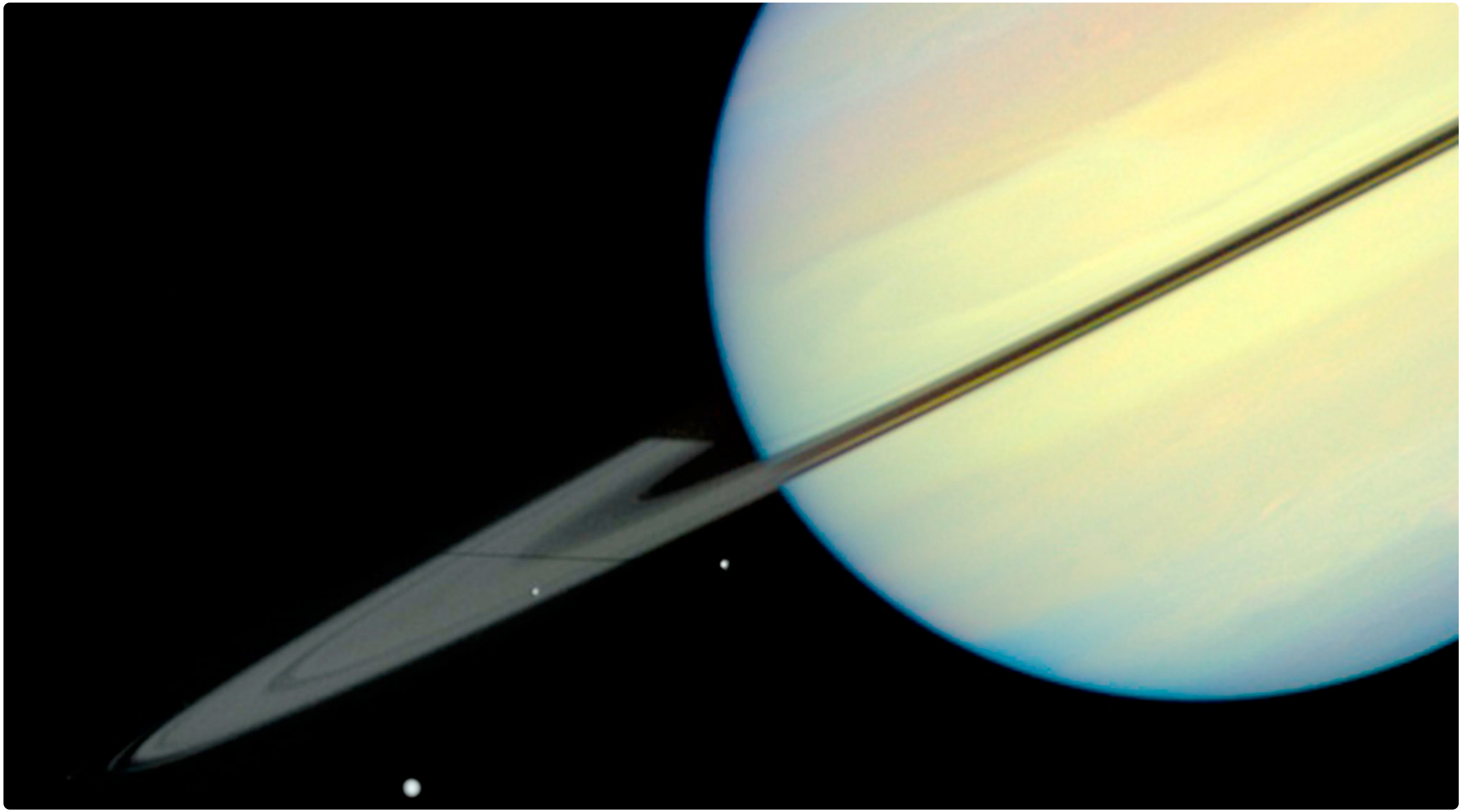
Ridges and valleys of dust mix with gaseous filaments glowing with ultraviolet radiation in NGC 2074 in the Large Magellanic Cloud.

Gallery 1.2 Cosmology

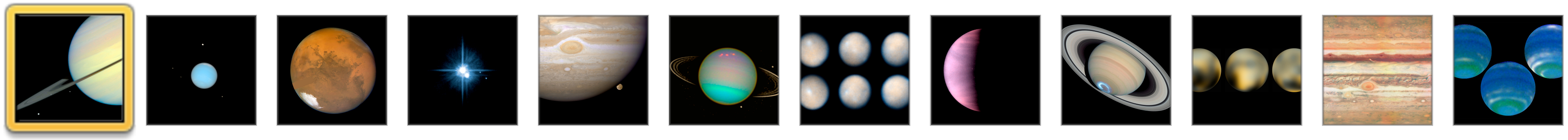
Starlight is shown in orange, hot gas in green, and dark matter in blue in this map of matter in galaxy cluster Abell 520.



Gallery 1.3 Planets



The shadow of one of Saturn's 62 known moons cuts across its rings in this image of the giant planet.



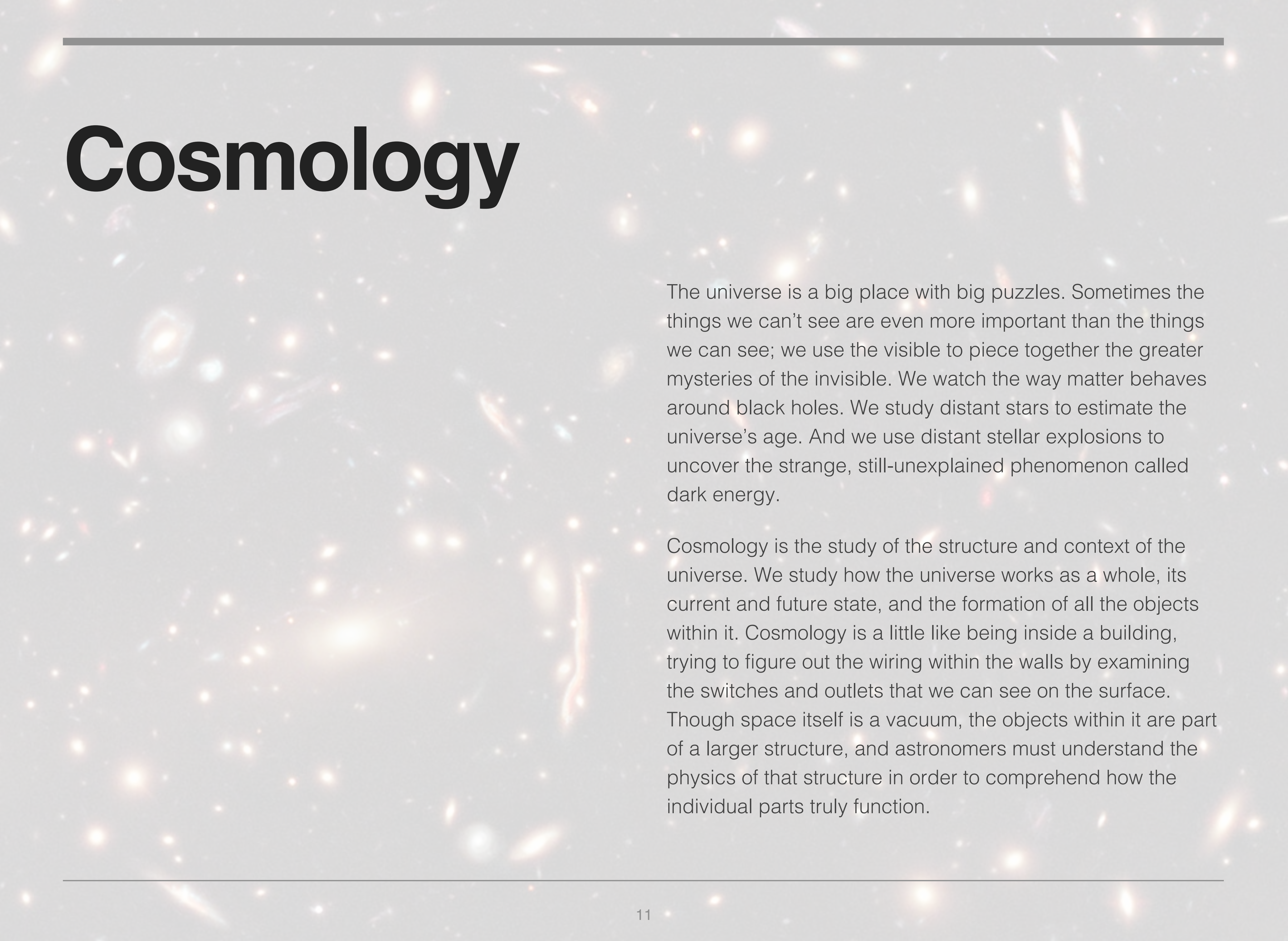
Gallery 1.4 Galaxies

Spiral galaxy M81, located about 11.6 million light-years away, is one of the brightest galaxies that can be seen from Earth.

CHAPTER 2

Cosmology

Galaxy Cluster MACS 1206

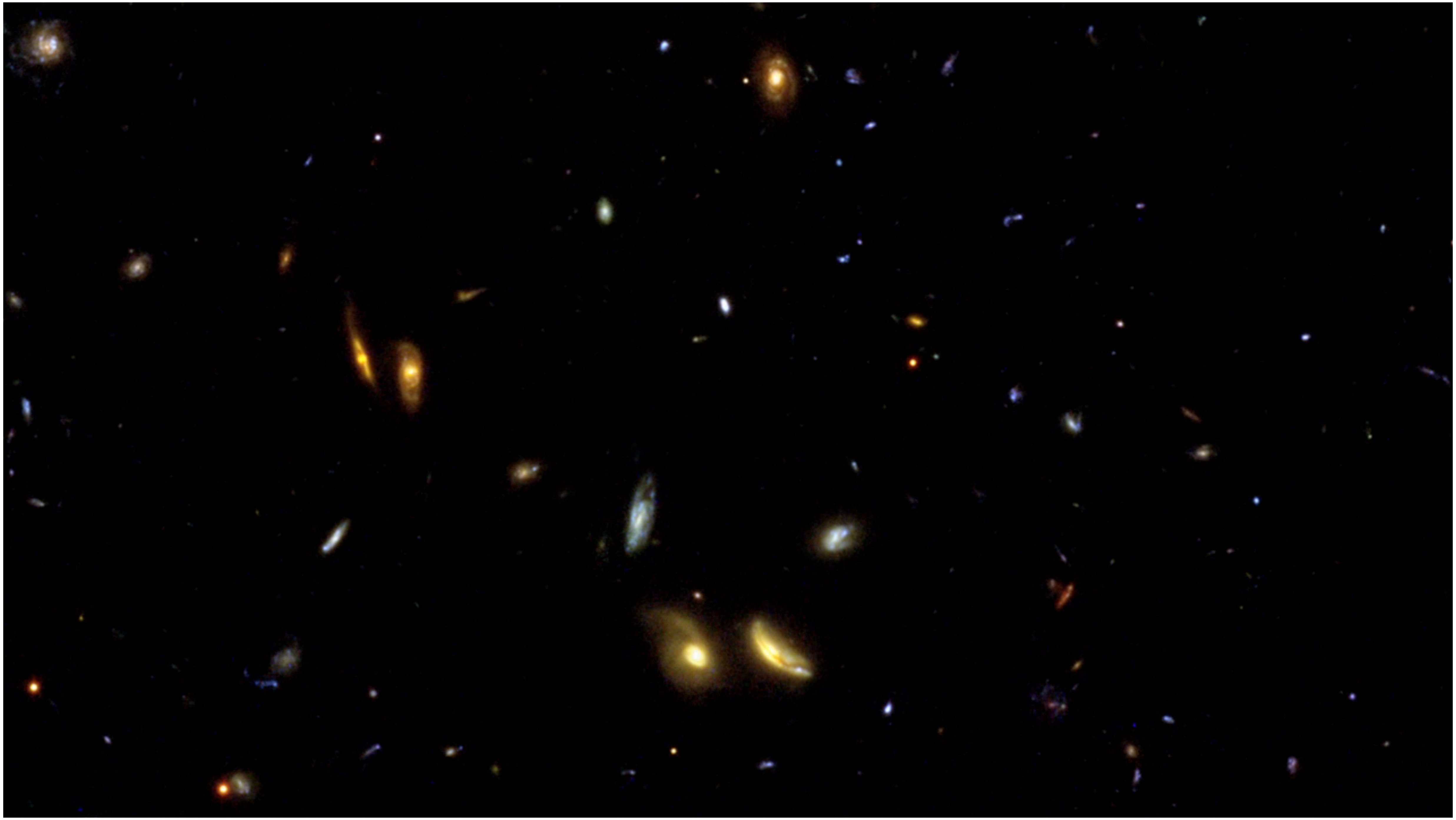


Cosmology

The universe is a big place with big puzzles. Sometimes the things we can't see are even more important than the things we can see; we use the visible to piece together the greater mysteries of the invisible. We watch the way matter behaves around black holes. We study distant stars to estimate the universe's age. And we use distant stellar explosions to uncover the strange, still-unexplained phenomenon called dark energy.

Cosmology is the study of the structure and context of the universe. We study how the universe works as a whole, its current and future state, and the formation of all the objects within it. Cosmology is a little like being inside a building, trying to figure out the wiring within the walls by examining the switches and outlets that we can see on the surface. Though space itself is a vacuum, the objects within it are part of a larger structure, and astronomers must understand the physics of that structure in order to comprehend how the individual parts truly function.

Taking Baby Pictures



Movie 2.1 Hubble: Galaxies Across Space and Time

When we look out at space, we are looking back in time. The light arriving at our location from the farthest objects in the universe is light that left those objects billions of years ago, so we see them as they appeared long ago.

So what do we see, when we capture the light from these farthest objects? The most distant galaxies look strange – smaller, irregular, lacking clearly defined shapes.

No telescope before Hubble had the resolution to see these distant galaxies. Intrigued, astronomers turned Hubble on what appeared to be a nearly empty patch of sky and took picture after picture for 10 days. They were taking a risk – most Hubble observations take just hours, and the time being eaten up could have been used for less speculative projects. It was possible the objects the astronomers were looking for would be too faint or small for even Hubble to see.

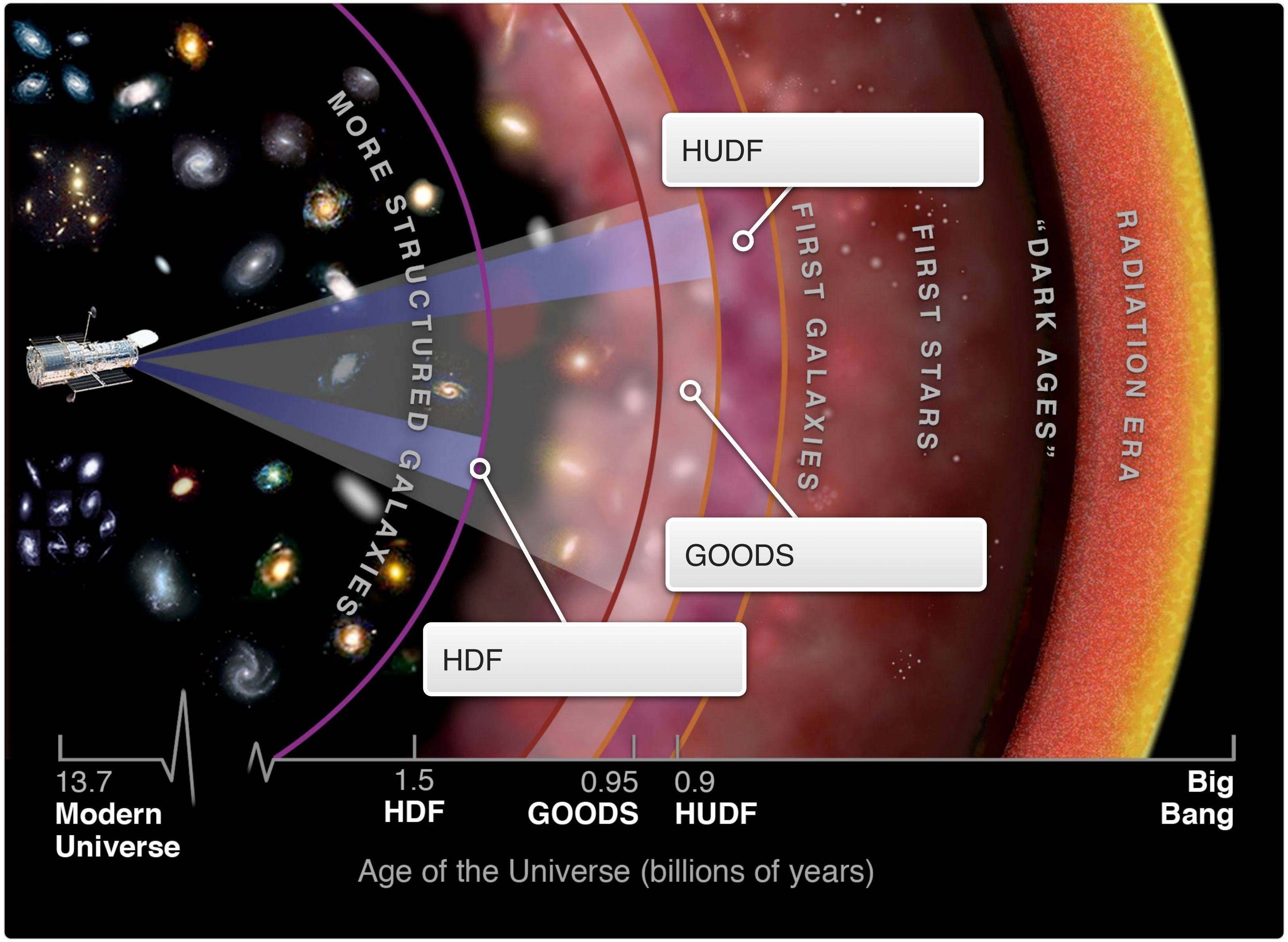
But the results turned up a treasure trove: 3,000 galaxies, large and small, shapely and amorphous, burning in the depths of space. The stunning image was called the Hubble Deep Field.

Gallery 2.1 Hubble's Deepest Views of the Universe Reveal a Multitude of Galaxies

Hubble Deep Field (HDF), 1995
– about 3,000 galaxies

Interactive 2.1 **Hubble Looks Back Through Time**

The deeper Hubble sees into space, the farther it gazes back in time. This chart illustrates the regions that have fallen under Hubble's eye and highlights some of the telescope's most significant deep-sky surveys.



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In subsequent years, Hubble teamed with other observatories to examine small patches of the sky in high resolution, long exposures, and multiple wavelengths.

Surveys like the Hubble Ultra Deep Field (HUDF) and the Great Observatories Origins Deep Survey (GOODS) have provided pictures of vast, deep collections of galaxies – including some that existed when the universe was less than a billion years old.

The images allow us to follow the development of the universe. Tiny red dots – early, shapeless galaxy building blocks whose light has been stretched by the expanding universe into an infrared glow – litter the most distant parts of the visible universe.

Closer in, we see numerous galaxy interactions and collisions as galaxies come together and merge, growing in the process. And nearer still, we see versions of the large, stately galaxies we know today.

The differences in these galaxies also help us learn about the initial stages of the universe – the part we can't really see. Their distribution and characteristics show that there was already some kind of structure in place when the galaxies began to form – or the spread of matter would have been even. Instead we see the coalescing of groups of matter, small pieces that formed and collided and merged. We don't quite understand yet how the universe went from a uniform void to an uneven cosmos ready for the formation of stars and galaxies, but looking back in time at the way galaxies have evolved gives us glimpses of the way the universe we know came about.

Interactive 2.2 **Galaxy Ages in the Hubble Ultra Deep Field**

Peel back the layers of time in the HUDF to reveal galaxies at different stages of evolution.

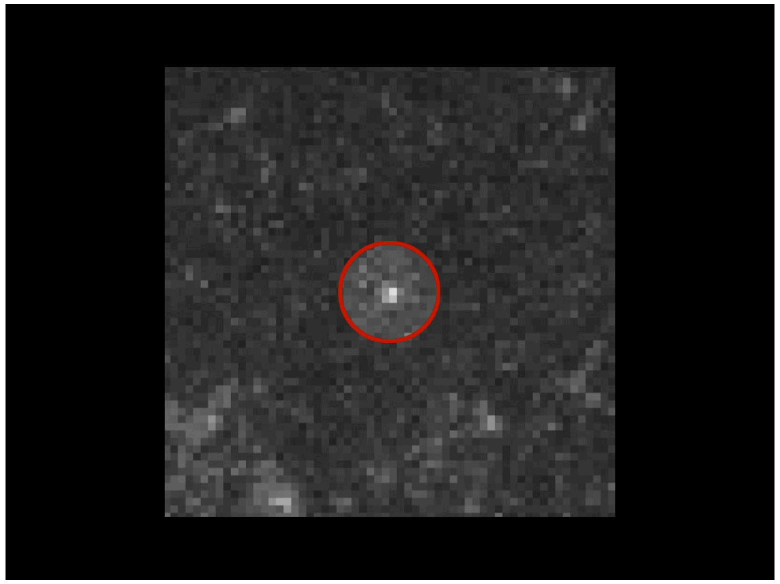
SECTION 2

Cosmic Birthday

An artist's impression shows how the very early universe (less than 1 billion years old) might have looked.

The answer to the age of the universe is beaming down on us from the sky. We know the universe has been expanding since the Big Bang, so if we can measure its size and its expansion rate, we can extrapolate the age of the universe.

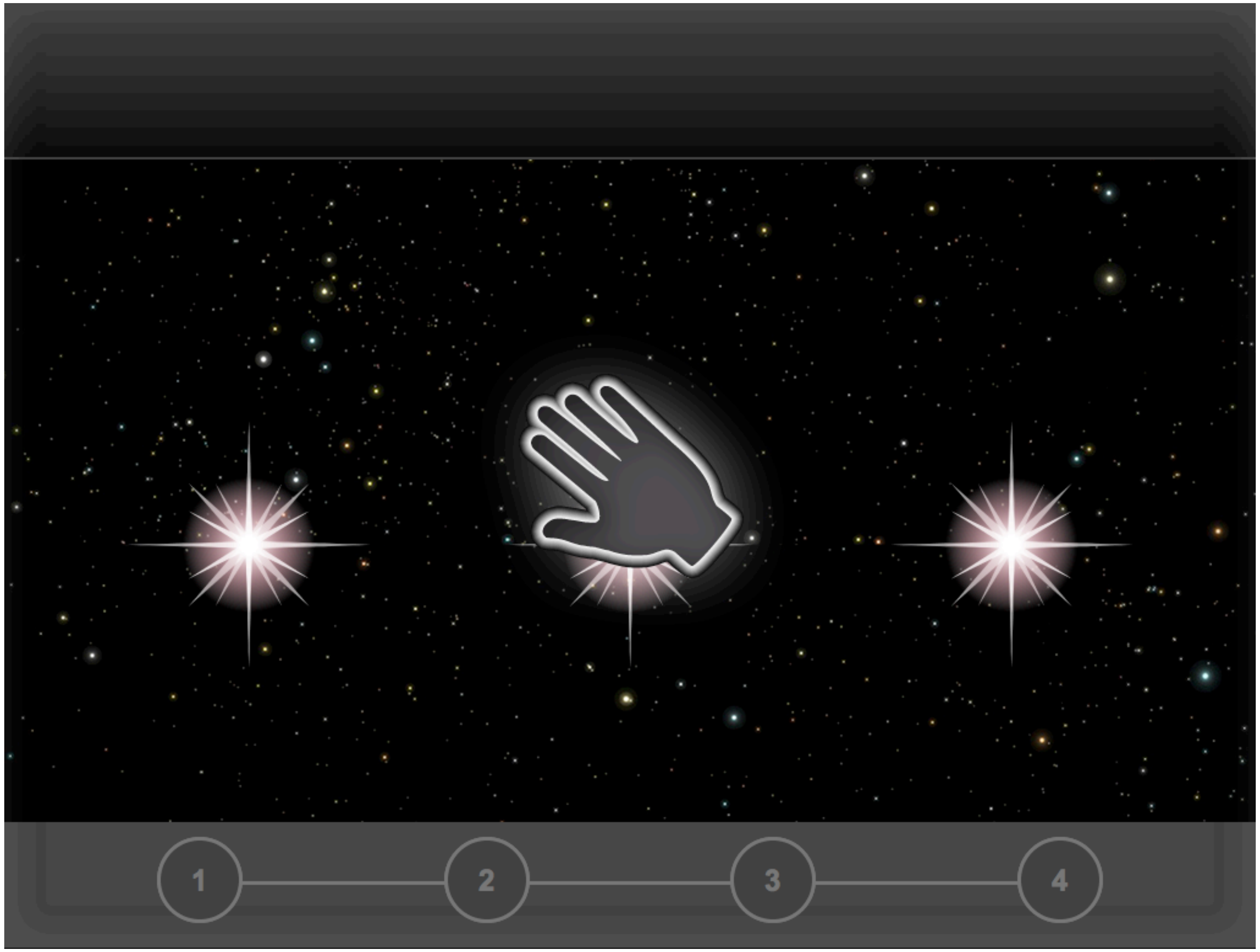
Interactive 2.3 Rhythmic Changes of a Cepheid Variable Star



This Cepheid variable star in galaxy M100 doubles in brightness through each pulsation. (Images captured by Hubble, April 23 – May 31,1994)

It's harder than it sounds. Since you can't extend a ruler out into the stars, all estimations are made by studying objects' brightness. Cepheid variable stars are a special type of pulsing star whose cycles of intensity and dimness indicate their inherent brightness. When astronomers find Cepheid variable stars in galaxies, they compare how bright they truly are with how faint they appear due to their great distances, and thus determine the distances to those galaxies. It's something like judging the distance to a car on a dark road by gauging the brightness of its headlights.

Interactive 2.4 Measuring Distances with Cepheids



Cepheid variable stars help astronomers measure distances in the depths of space. Learn how pulsating stars function as yardsticks for the universe.

Figure 2.1 **Galaxy NGC 4603, Home to Cepheid Variable Stars**

NGC 4603 is the most distant galaxy – 108 million light-years away – in which Cepheid variables have been found. From Earth, its stars appear very faint. So, accurately distinguishing the characteristics of the Cepheids found within NGC 4603 is extremely difficult. Researchers used these Cepheids to securely determine the distance to the galaxy.

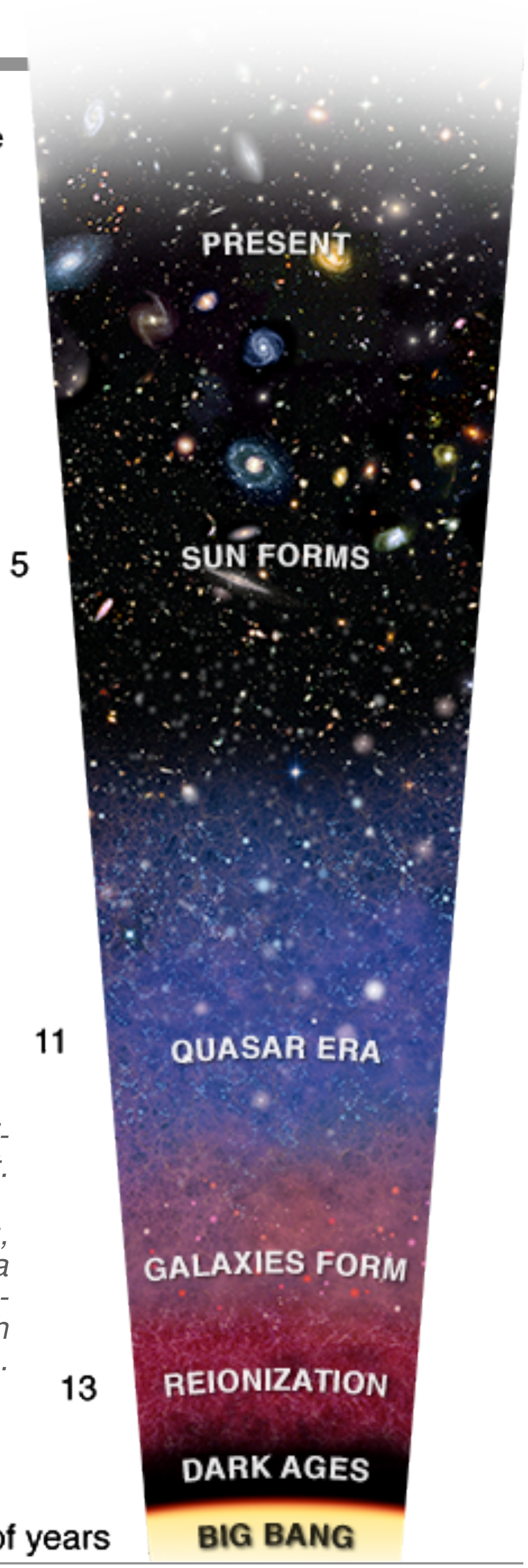
Before Hubble, astronomers had only been able to narrow the universe’s age down to 10-20 billion years old – not a particularly exact measurement with 10 billion years of leeway.

Hubble performed the definitive study of 31 Cepheid variable stars, helping to determine the current expansion rate and narrow the age of the universe down to the most accurate it’s ever been. Its observations of Cepheid variable stars in galaxies like NGC 4603, combined with measurements by other observatories, eventually pinned the age down to 13.7 billion years old, plus or minus a few hundred million years. Hubble’s observations helped change the age of the universe from a vast range of possibilities to the kind of number whose precision required a decimal point.

Knowing the age of the universe isn’t just a matter of curiosity. By giving us a time scale for the development of stars and galaxies, it helps us refine our models of how the universe – and everything in it – formed.

A solid age for the universe pulled numerous elements of cosmology into shape. We need an age in order to understand the timelines for star and galaxy formation – previous problems with the universe’s age range included conflicts like stars thought to be older than the universe itself. Now that we have an age, we can determine everything from the time needed for the life cycle of stars to the time needed for stars to form elements such as carbon, nitrogen and oxygen – elements we need to exist.

History of the Universe



A representation of the evolution of the universe over its 13.7-billion-year history, from the Big Bang to the present.

Two watershed epochs are shown. Not long after the Big Bang, light from the first stars burned off a fog of cold hydrogen in a process called reionization. At a later epoch quasars, the black-hole-powered cores of active galaxies, pumped out enough ultraviolet light to reionize the primordial helium.

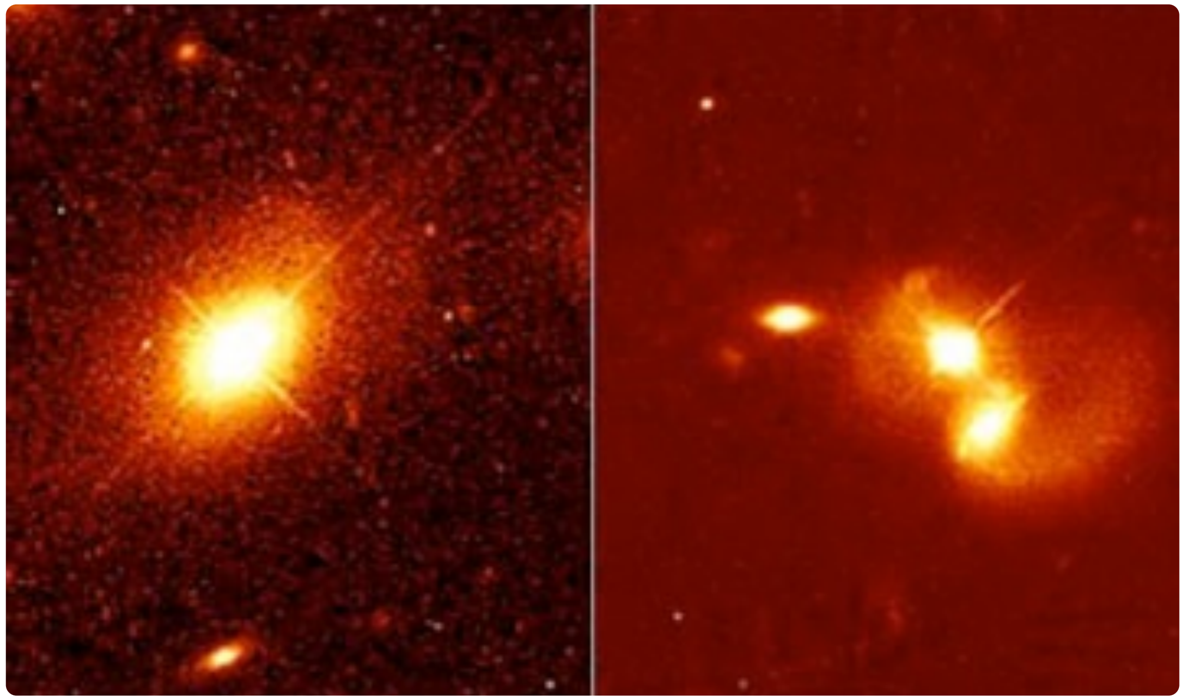
SECTION 3

Lurking Black Holes

A supermassive black hole creates a jet of particles that travels at nearly the speed of light from the center of galaxy M87. The jet bursts forth from the disk of material swirling around the black hole.

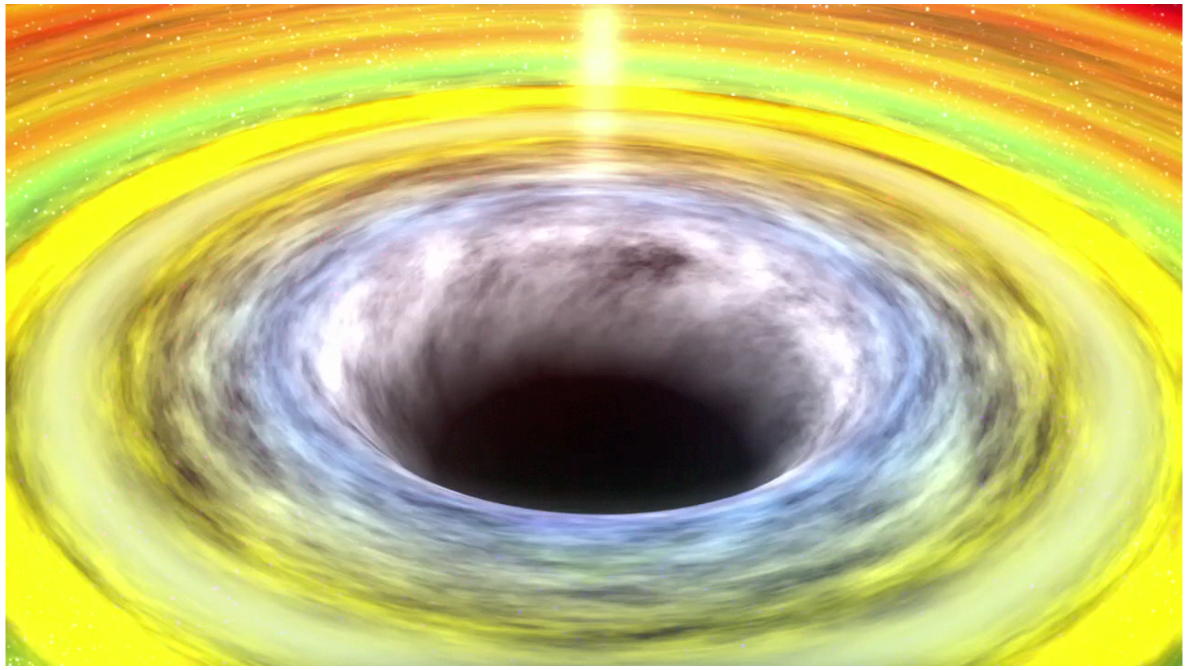
When astronomers first turned radio telescopes on the sky, they tracked radio wave sources to some typical cosmic objects, including the remains of supernovae, distant galaxies, and powerful areas of star birth. But one particular type of object looked like nothing more than a point of light, perhaps a star. Further observations showed that these

Figure 2.2 Quasar Host Galaxies



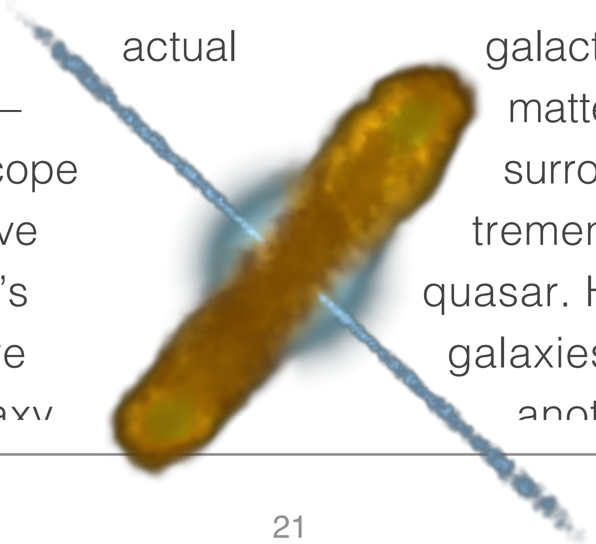
Quasars shine from both single (left) and colliding galaxies (right) in these images. The galaxies are 1.5 billion and 1.6 billion light-years away, respectively.

Movie 2.2 Black Hole Accretion Disk Energies



A black hole is a massive object whose gravity is so intense that nothing – not even light – can escape once it has passed the border known as the event horizon. Accretion disks of hot material encircle many black holes, and this material emits X-rays and other forms of energy. Oppositely directed jets of gas often form in the innermost zone of black hole accretion disks.

objects were extremely far away, meaning they could only be distant galaxies. The objects, called “quasars,” were thought to be the incredibly bright centers of those faraway galaxies.



The distance to quasars is so great, and their actual size so small – about the size of our solar system – that the mere fact that we can see them via telescope makes quasars some of the brightest objects we’ve discovered in the universe. In fact, one of Hubble’s contributions to the quasar mystery was to prove with its high resolution there actually was a galaxy hidden behind the glare.

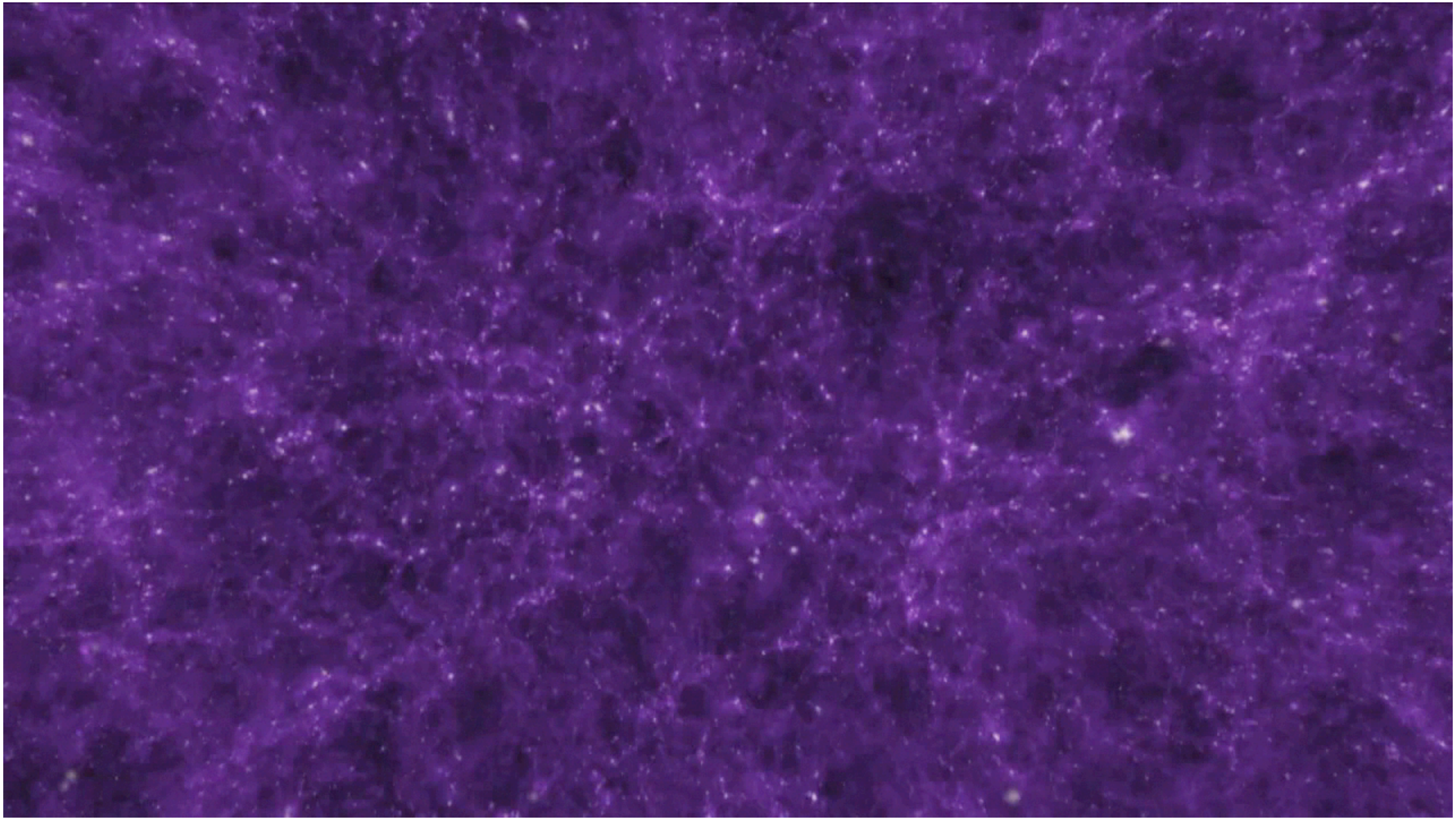
Hubble observations also helped determine that these brilliant galactic centers are powered by giant black holes. As matter falls into a supermassive black hole, the surrounding region heats up and releases tremendous amounts of energy and light, creating a quasar. Hubble found quasars in the centers of galaxies that are colliding or brushing up against one another, as well as in elliptical galaxies, which are thought to have developed as a result of multiple galactic mergers. These interactions may help “feed” the central black hole and light up the quasar.

And it wasn’t just quasars. Hubble found that almost all galaxies with bright, active centers have supermassive black holes feeding off the galaxy’s matter. Further, the mass of the black hole is related to the mass of the bulge of stars around the center of the galaxy, indicating that the formation of a galaxy is closely connected to the formation of its black hole.

The study of these monstrous black holes leads us to many questions about the formation of galaxies and the structure of the universe – why did some regions of the universe form galaxies with massive black holes, and others form rather ordinary galaxies? Are quasars just a stage in the formation of supermassive black holes? And why does the black hole phenomenon exist over such a wide range of sizes, from giant black holes in the center of galaxies to small black holes a few times larger than our Sun?

This artist’s conception illustrates a supermassive black hole (central black dot) at the core of a young, star-rich galaxy.

The Runaway Universe

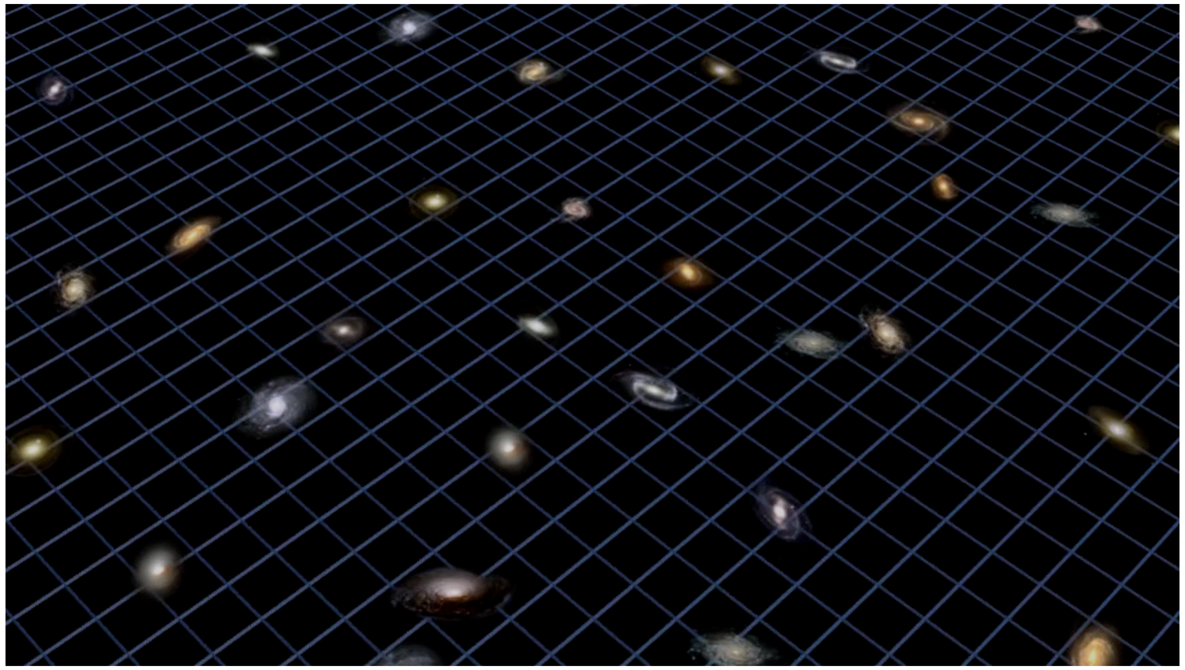


Movie 2.3 **Dark Matter and Galaxies Form as the "Cosmic Web"**

Our universe started with a bang and has been expanding ever since, the space between galaxies increasing with time. For many years, astronomers contemplating the death of the universe considered two main possibilities: either the universe would go on expanding forever, the galaxies gently drifting apart; or the universe would stop expanding and fall back on itself in a “big crunch.”

By the late 20th century, astronomers were confident the answer was that the universe would expand forever at a constantly decreasing speed, coasting like a car out of gas but never quite running out of momentum. They began working to determine the rate of the expansion.

Movie 2.4 **Possible Fates of the Universe: Big Crunch**



Movie 2.5 **Possible Fates of the Universe: Slow Drift**

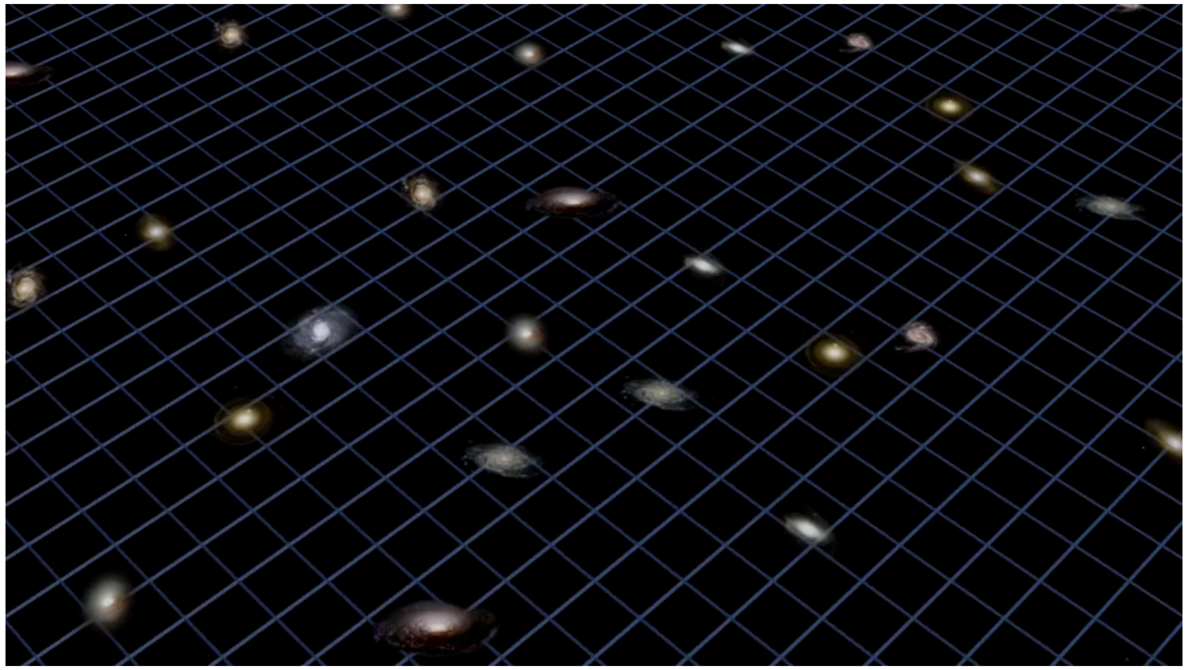
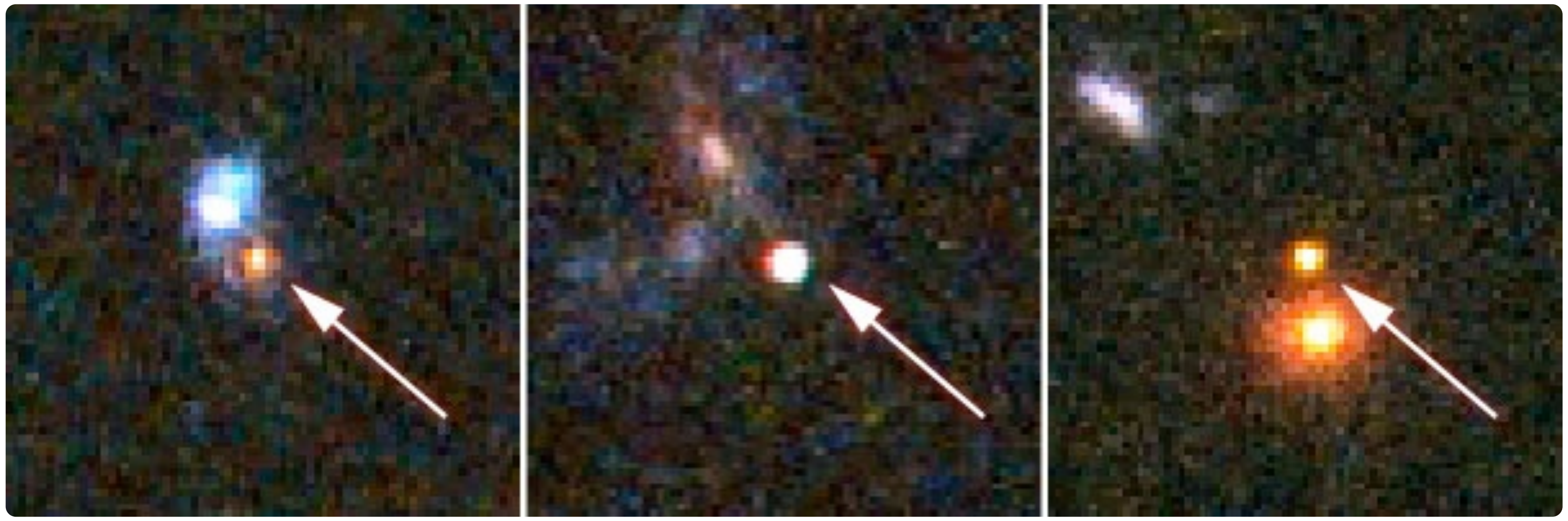
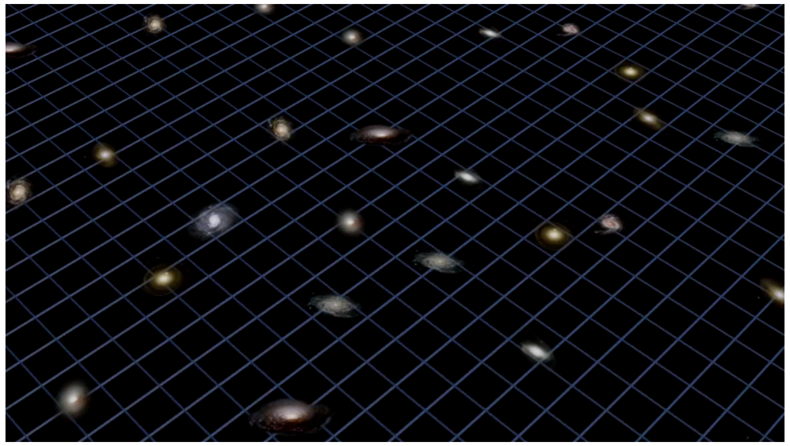


Figure 2.3 **Supernovae Spotted in Distant Galaxies**



Movie 2.6 **Possible Fates of the Universe: Dark Energy**



Like Cepheid variable stars, the brilliant stellar explosions known as supernovae could be used to find the distances to galaxies. But because of their incredible brightness, supernovae can be used to measure even farther distances than Cepheids. Hubble's clear vision allowed astronomers to find the extremely distant supernovae needed to measure the expansion rate of the universe. But Hubble's observations threw the standard assumptions into disarray: the universe wasn't slowing down at all. Examining the properties of the supernovae Hubble had imaged, astronomers found that the universe was speeding up as though something were propelling it, driving its expansion faster and faster.

What is it? Scientists still don't know. Some suspect a previously unknown "dark energy" is the culprit, but this is a field whose puzzles are just becoming visible to humanity. Whatever causes this acceleration doesn't seem to be part of the glowing matter we can see, so it'll take some time to understand its true nature. The challenge now is to develop tests for a phenomenon invisible to us, tests that will allow us to describe and define dark energy until it's as clear to us as the stars in our own backyard. For now, Hubble continues to study the supernovae that could be the key to solving this mystery.

Discovering Dark Energy

Certain types of exploding stars, called Type 1a supernovae, always give off about the same amount of light. This makes the brightness of these explosions nearly identical.

So when Type 1a supernovae appear to vary in brightness, it must be because some are closer to us, and some are farther away. Astronomers can compare the true brightness of the supernovae with their apparent brightness, and calculate the distances to the supernovae. This also gives the distance to the galaxies in which the supernovae occurred.

Astronomers thought the expansion of the universe should be slowing down, and expected the distances to faraway galaxies to back that up. But Hubble found that the most distant supernovae were dimmer than they should have been, meaning they and their galaxies were farther away than expected.

The greater distances contradicted the hypothesis that the universe's expansion was slowing or even staying at a constant rate. Their distance only made sense if the expanding universe was actually speeding up. The discovery won the scientists involved the 2011 Nobel Prize in Physics.

Figure 2.4 Comparing the True and Apparent Brightness of Supernovae

The apparent brightness of Type 1a supernovae gives cosmologists a way to measure the expansion rate of the universe at different times in the past.

CHAPTER 3

Galactic Science

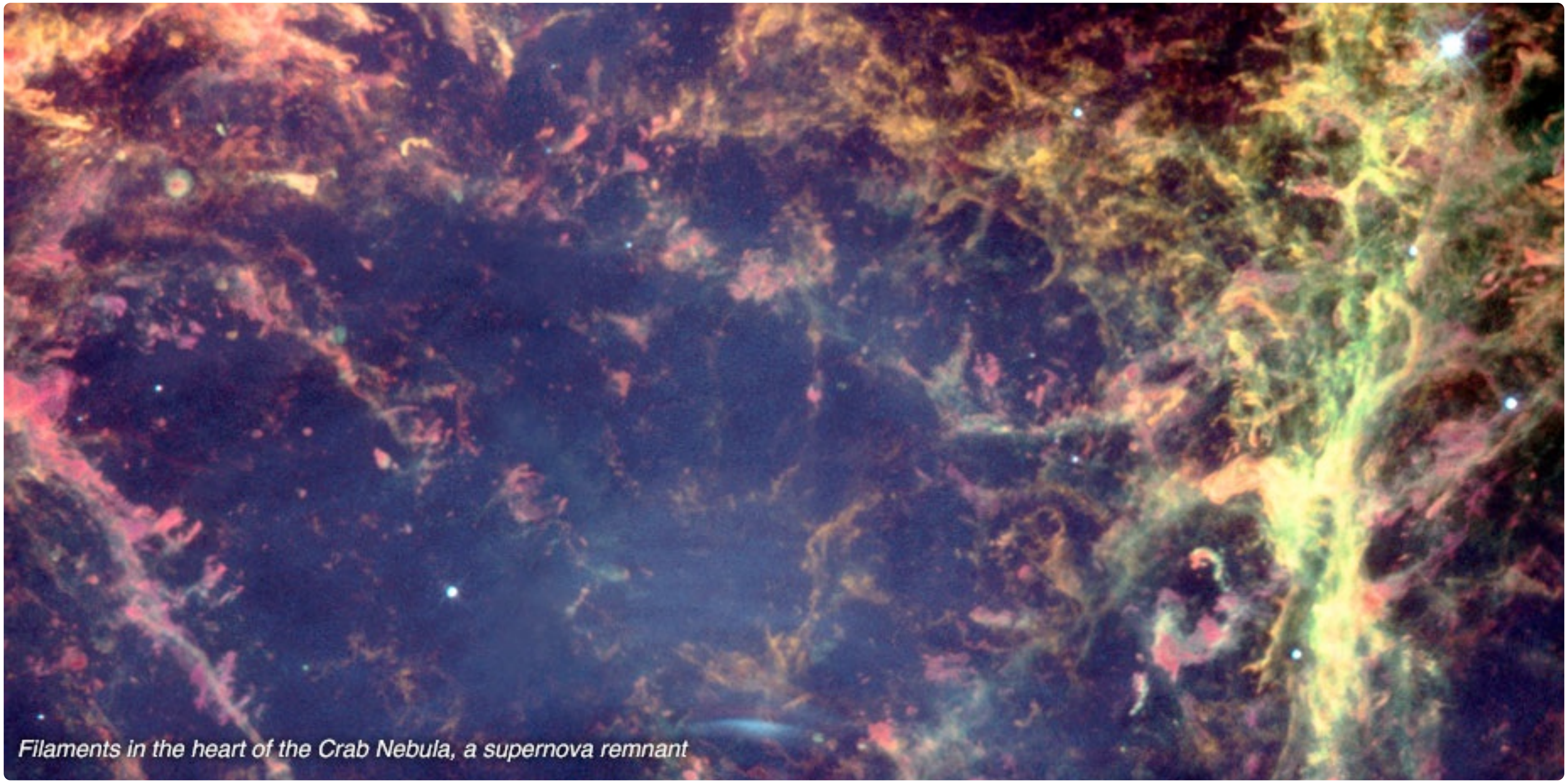
The Antennae Galaxies

Galactic Science

Galaxies are where the action happens in space, islands of activity in a sea of emptiness. Our Milky Way galaxy is a vast spiral disk of 100 billion to 400 billion stars, so huge that we will never be able to travel long enough to view it from the outside. But we can watch the activity within our own galaxy, and gaze through space to observe the interactions of galaxies far away. Hubble has helped identify the sources of the universe’s most powerful explosions, learned how galaxies came to be, and observed stars in the last stages of their lives.

Our observations of galaxies present the universe in its most clear and visible form. We watch the dynamics of the cosmos, how things form and change, through our study of galaxies. We witness dominant galaxies cannibalizing their surroundings and stars forming under the influence of galactic gravitational forces, and we puzzle over the numerous shapes that galaxies take. Our little solar system resides within a galaxy, and the study of galaxies past and present are key to our understanding of the forces that shape our existence.

Gone in a Flash



Filaments in the heart of the Crab Nebula, a supernova remnant

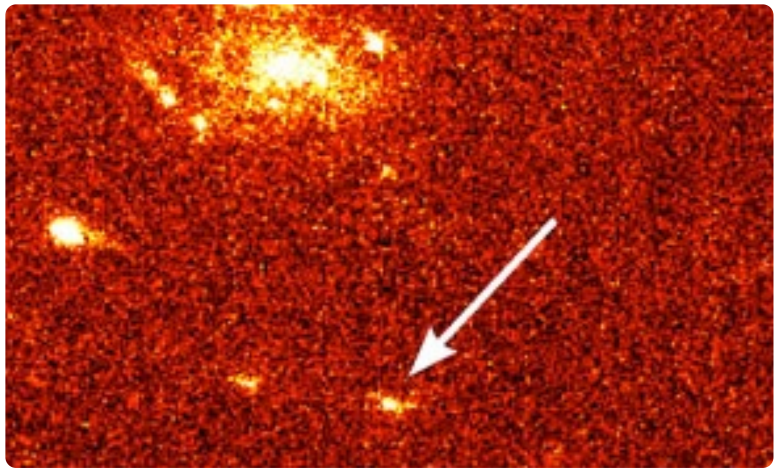
In the 1960s, the United States Air Force launched a series of satellites to monitor gamma rays. The Nuclear Test Ban Treaty had just been signed, and the U.S. wanted to watch for the telltale radiation emitted by nuclear blasts.

The satellites quickly began picking up gamma-ray events – but the study rapidly ruled out bombs as a source. In fact, the bursts had no ties to Earth at all. As scientists investigated further, they slowly realized what they were seeing: explosions with the power of 10 million billion Suns, that took place on a daily basis, emanating from seemingly random points within the cosmos. They were witnessing the universe's most ferocious explosions, undetected until then.

Movie 3.1 What Are Gamma Rays?

Scientists explain the extreme events that produce gamma rays and why we look for them.

Figure 3.1 Gamma-Ray Burst 971214



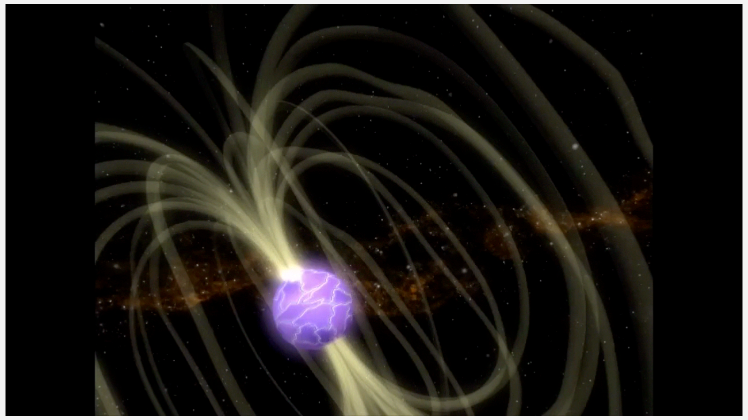
The galaxy in this image, 12 billion light-years from Earth, gave off a gamma-ray burst in 1998 that was as bright as the entire rest of the universe for one or two seconds. Astronomers had never before witnessed such a swift and enormous release of energy.

Figure 3.2 Gamma-Ray Burst 080319B

For nearly a minute this single object was as bright as 10 million galaxies during a powerful gamma-ray burst in 2008.

Observatories followed up on the mystery and came to the conclusion that the bursts came from supernovae, the explosions of massive stars that can end in the formation of a black hole or neutron star. But not all supernovae produced gamma-ray bursts – what was the true cause?

Movie 3.2 Closeup of a Neutron Star



This artist's conception illustrates a neutron star and its magnetic field lines cycling before, during and after a gamma-ray burst.

Scientists now know there are at least two different kinds of gamma-ray bursts. Hubble observations have helped discover that a large proportion of gamma-ray bursts originate in the brightest star-forming regions that also have stars low in metal content. It appears that the process of creating a supernova from a star that contains lots of metal, and a star that contains little, may be different. One idea is that stars with low metal content tend to retain more mass upon their death, producing black holes, while stars with high metal content form neutron stars instead. If that's true, it may be that the gamma-ray burst is often the birth announcement of a black hole.

Gamma-ray bursts give us another piece of the supernovae puzzle. By witnessing the explosion in action, we can work backwards to determine how it happened. Since supernovae provide one of the few methods astronomers have for measuring vast distances in space, understanding these titanic explosions is critical to our comprehension of the universe.

Gallery 3.1 Sheets of Debris from Stellar Explosions

Filaments of gas and dust surround a neutron star, all that's left after a supernova explosion. Decades before this observation of N49 was taken, this neutron star gave off a tremendous gamma-ray burst measured by numerous satellites.

Tracing Galactic Histories

Movie 3.3 A Night Sky View During the Future Milky Way and Andromeda Galaxy Merger (animation)

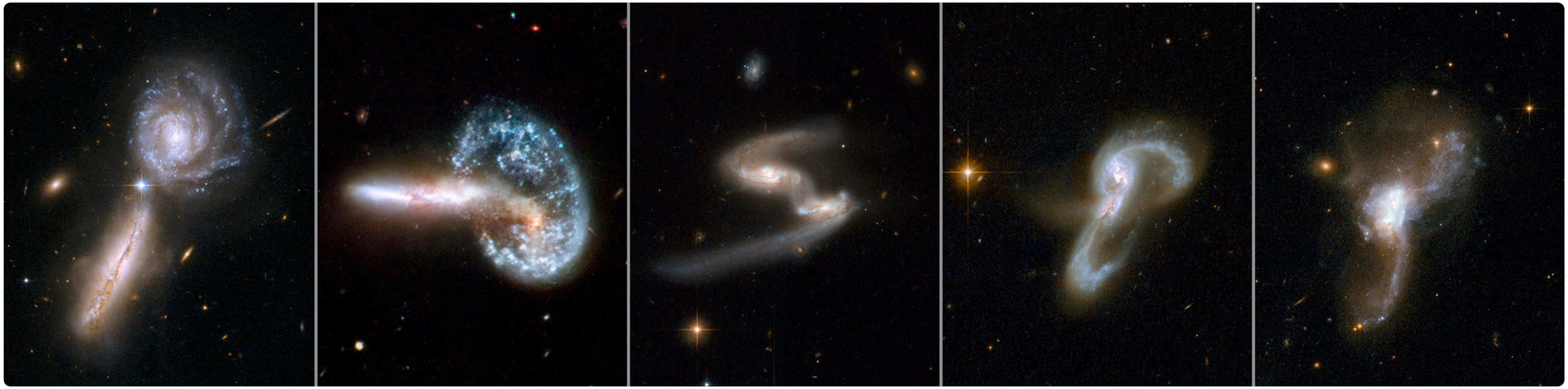
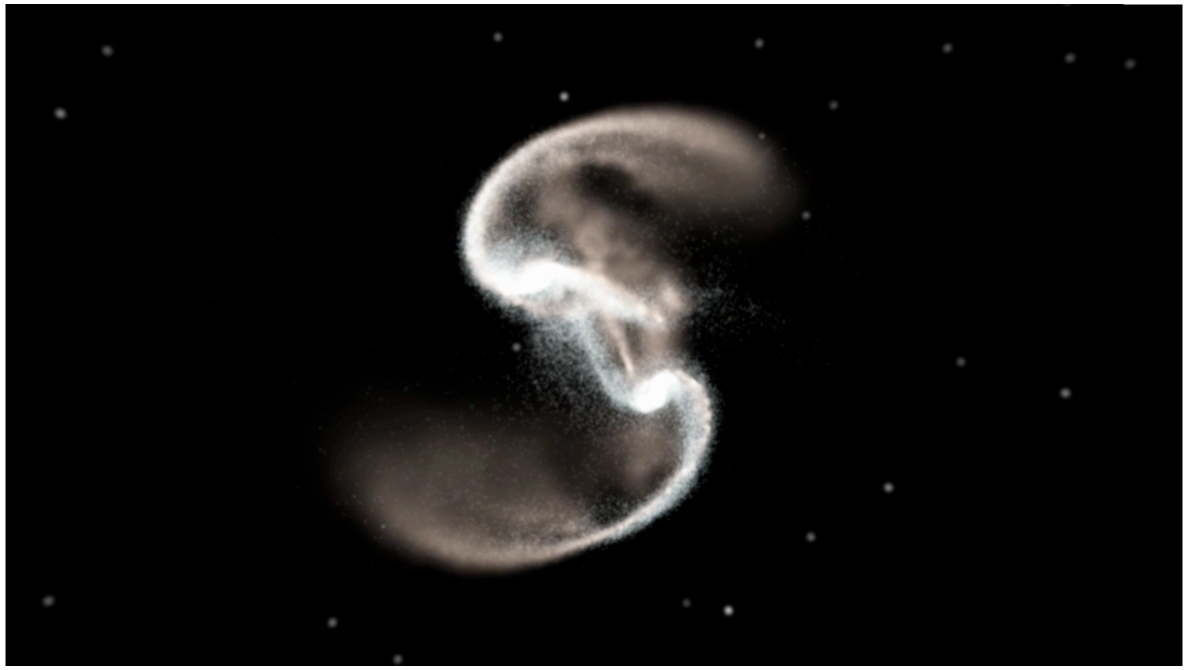


Figure 3.3 **Interacting Galaxies**

Galaxies, drawn to one another by gravity, can often collide and merge. Such interactions happened more frequently in the early universe than they do today, and astronomers believe that these galactic crashes are an important way that galaxies grow and evolve.

Our own Milky Way galaxy, and its neighbor Andromeda, must have grown by absorbing smaller, nearby galaxies. We can test this hypothesis by studying the ages, arrangements, compositions and speeds of stars in a galaxy.

Movie 3.4 **Different Stages in the Collisions Between Galaxies**

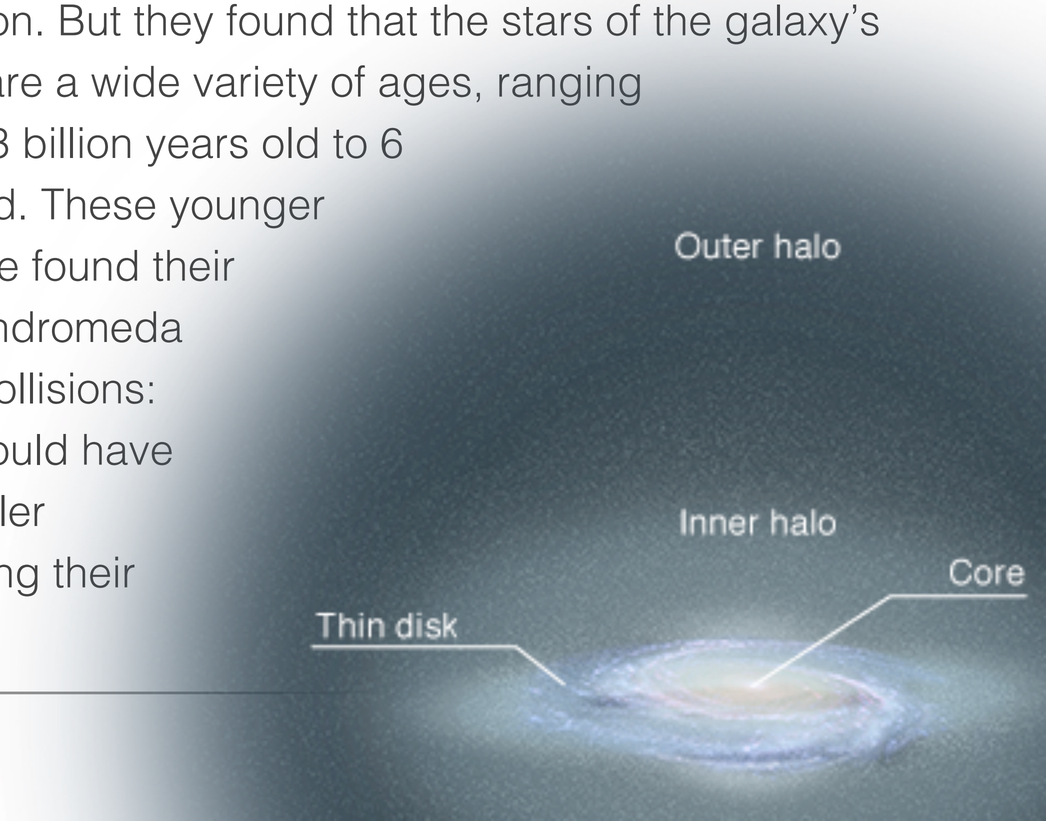


This supercomputer simulation shows an entire galaxy collision sequence, and compares different stages of collision to a variety of interacting galaxy pairs observed by Hubble. With this combination of research simulations and high-resolution observations, these titanic crashes can be better understood.

Figure 3.4 **Hubble Observes 300,000 Stars – Young and Old – in Andromeda's Halo**

Hubble observed the Andromeda galaxy's halo, that region of stars on the outskirts of the galaxy, beyond the main galactic disk. Andromeda is the closest large galaxy to our Milky Way, and while it has been observed frequently from the ground, Hubble's resolution is powerful enough to see its individual stars.

Astronomers expected that the stars in Andromeda's halo would be old, since halos are thought to develop early during galaxy formation. But they found that the stars of the galaxy's outer regions are a wide variety of ages, ranging from around 13 billion years old to 6 billion years old. These younger stars must have found their way into the Andromeda halo through collisions: Andromeda would have eaten the smaller galaxies, making their stars its own.



Hubble’s observations provide strong support that galaxy interactions and mergers are a standard part of the history of all large galaxies.

And someday, we’ll be able to experience that fact firsthand. Hubble has revealed that the Milky Way and Andromeda galaxy are on a direct collision course. In 4 billion years, the two mammoth galaxies will slam into each other, spinning together in a slow, massive dance and eventually combining into a single new galaxy.

Astronomers made precise observations of the sideways motion of the Andromeda galaxy over five to seven years. Astronomers have known for years that Andromeda and the Milky Way were headed toward one another, but whether they would collide, brush by one another, or miss one another was an open question.

Movie 3.5 Hubblecast: Crash of the Titans

Scientists explain how they use Hubble observations to predict the future of the Milky Way and Andromeda galaxies. Computer simulations based on the observations predict the two galaxies will crash together in about 4 billion years.

When the collision happens, the Sun will be flung into a new region of the galaxy, but Earth and its companion planets will continue on, serenely unaffected. When galaxies collide, stars change their orbits, but the distances between stars are so vast that there’s little danger of stars striking one another.

Dying Stars

The Egg Nebula is an example of a planetary nebula.

Mid-sized stars like our Sun end their lives by ejecting their outer layers of gas into space over the course of about 30,000 years, leaving behind the star's hot core – a white dwarf.

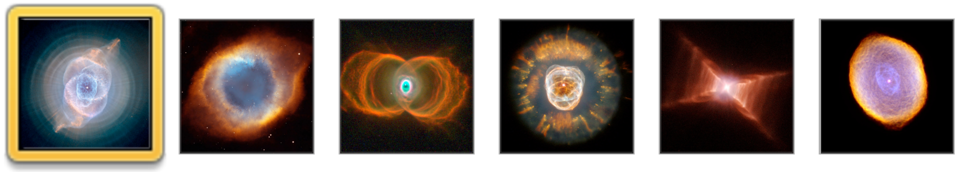
Radiation from the white dwarf heats the gas and causes it to glow, creating a unique and beautiful formation called a planetary nebula. The name comes from the early days of astronomy, when observers thought the dim forms they saw through their telescopes might be related to planets.

Today, Hubble has observed many of these nebulae and found a wide range of complicated and extraordinary shapes, from tunnels to interlocking rings. The Cat's Eye Nebula, for example, consists of 11 bubbles of gas, each appearing from our perspective as a ring. Hubble's observations show that planetary nebulae are formed in multiple outbursts, not just in one dying breath, since we can see the previously exuded material interacting with newly ejected material.

Movie 3.6 Pan Across the Glowing Gas of Planetary Nebula NGC 6302

Gallery 3.2 A Gallery of Planetary Nebulae

The Cat's Eye Nebula (NGC 6543)



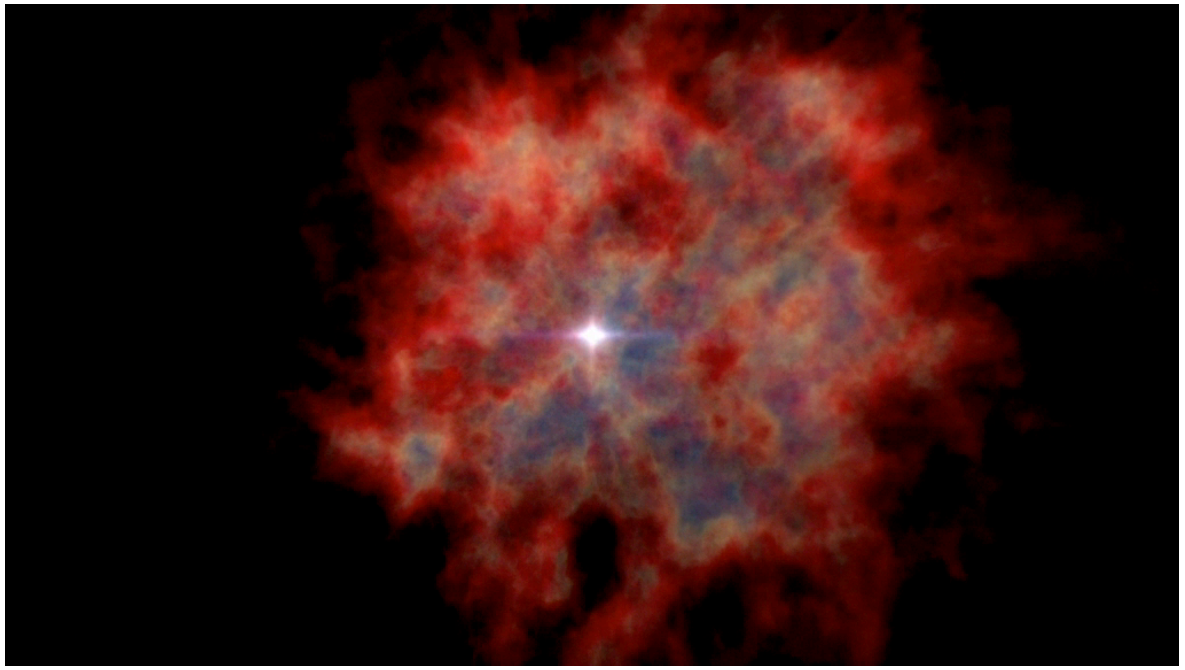
Movie 3.7 **The Helix Nebula's 3D Structure (visualization)**

Planetary nebulae appear flat from our viewpoint, but they're much more complex than that. Evidence suggests that the Helix Nebula consists of two disks nearly perpendicular to each other.

Though the dynamics that create such intricate structures in a relatively short time are still mysterious, each Hubble image helps us understand a little more about how Sun-like stars spend their final years. And planetary nebulae aren't just good for pretty pictures: Sun-like stars produce the elements of carbon, nitrogen, oxygen and iron, vital to life as we know it, within their cores. By studying their deaths, we learn how these elements are spread throughout the universe.

A star eight to 25 times more massive than our Sun ends its life in another way – in a tremendous explosion, called a supernova, which may leave behind a neutron star or a black hole. When these massive stars exhaust their fuel, their cores collapse and explode, sending their outer layers speeding into space.

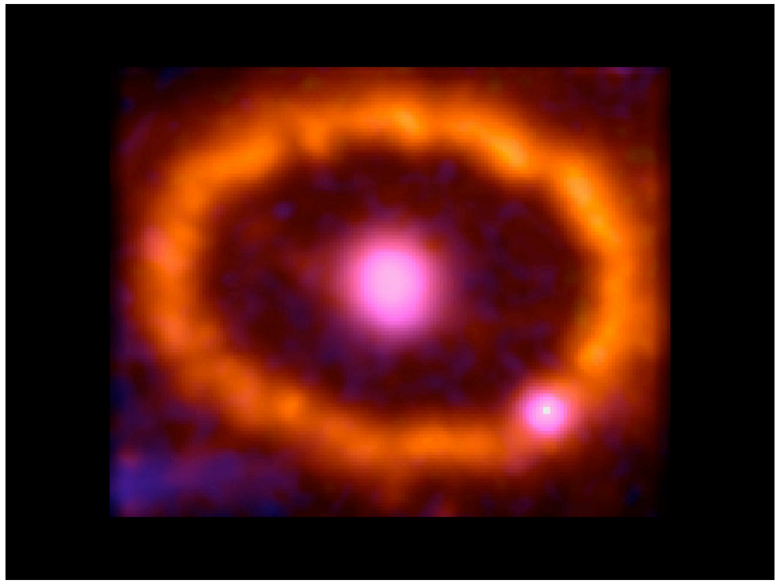
Movie 3.8 **A Supernova with an Expanding Shell (animation)**



A massive star ends its life in a titanic explosion called a supernova. A supernova blasts the material of the star across interstellar space at millions of miles per hour. Elements formed inside the star during its lifetime are then scattered across space to become parts of future nebulae, stars and planetary systems.

The last time astronomers observed a supernova in our galaxy was in the 1600s, when Europe was still in the process of colonizing North America. But in 1987, the light from a supernova in one of the Milky Way's satellite galaxies, the Large Magellanic Cloud, reached Earth. Three years later, upon its launch, Hubble began to monitor the explosion from the first-ever ringside seat for a supernova.

Interactive 3.1 Stellar Blast from Supernova 1987A (1994 – 2006)



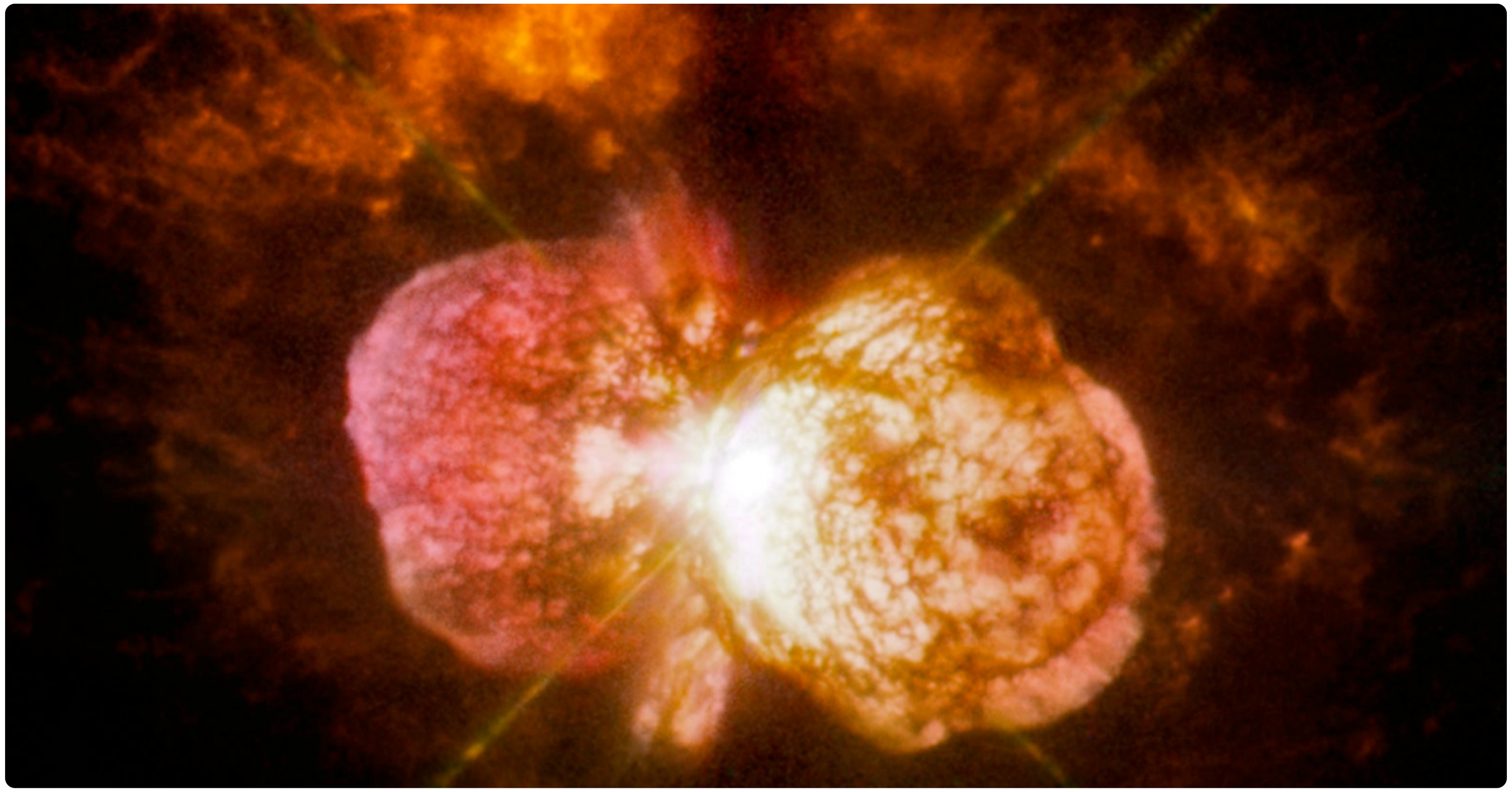
Shock waves of material unleashed by the stellar explosion are illuminating a 6-trillion-mile ring of gas around the dying star.

Hubble has observed Supernova 1987A repeatedly, witnessing rings and knots of gas brightening around the exploded star. Watching the supernova in progress for over two decades has led to a greater understanding of how these events play out over thousands of years.

Hubble has also monitored a supernova in the making. Eta Carinae is a supermassive star, more than 100 times the mass of the Sun, or a pair of supermassive stars. In 1843, it briefly became the second brightest star in our night sky. Hubble images revealed that the unstable star had blasted out two lobes of hot gas, a prelude to its ultimate explosive end. Eta Carinae is so massive that scientists think it could end its life as a "hypernova," a kind of extra-powerful supernova that could outshine the entire galaxy.

Massive stars produce all the elements we know that are heavier than iron, and when they die that material is spewed through space. The gold ring on your finger or the titanium in your watchband are indications that our solar system was once flooded with material from supernovae.

Figure 3.5 The Doomed Star Eta Carinae



Astronomers expect the unstable star, Eta Carinae, will someday explode in a supernova. An outburst 150 years ago produced the lobes of gas racing outward at 1.5 million miles (2.4 million km) per hour.

CHAPTER 4

Planetary Science

Artist’s View of Extrasolar Planet HD 189733b

Planetary Science

What happens on the surfaces of our closest neighbors? Farther away, are there places like our own, with their own populations wondering at the skies? Hubble has watched stars and planetary systems in the making, examined the atmospheres of planets around distant stars, and witnessed the destructive power of cosmic impacts.

Our understanding of planetary science expands tremendously with every bit of information we can collect and each new planet we discover. Our original roster of planets – just nine, if you include Kuiper Belt Object Pluto – is an extremely small sample to form conclusions upon. The detection of extrasolar planets – planets beyond our solar system – has amazed astronomers with the diversity of planetary systems: giant planets hovering close to their home stars, planets in strange, elongated orbits, even a planet orbiting two stars at the same time. The more we see of planets within our solar system and beyond, the more information we glean on how these bodies came into existence, and the more we understand about our own Earth.

Birth of Stars and Planets

Infant stars buried inside a pillar in the Carina Nebula fire off jets of gas seen streaming from towering peaks.

New stars form out of collapsing clouds of gas and dust, as gravity pulls material together into a dense object surrounded by a spinning disk of leftover matter. Eventually, the young star erupts with jets of intense radiation trillions of miles long, traveling at 500,000 miles (800,000 km) per hour. Scientists are still unsure exactly how the jets form, but believe they

Gallery 4.1 Narrow Jets Erupt During Stellar Formation

Stellar jet, HH 47, shoots off at supersonic speeds in opposite directions through space.

result from magnetic fields emanating from and rotating around the forming star.

Before Hubble, astronomers could see the jets, but not the star-forming disks. Hubble’s vision allowed them to see both. In 1995, it took the first detailed images of jets and disks in the Orion Nebula.

Hubble has since taken many images of jets, and found the first direct evidence that they originate at the center of the dusty, gaseous disk the forming star is drawing upon for its raw material. The jets are thought to play a major part in star formation, perhaps slowing down the spinning disk so more matter can collect onto the star.

Figure 4.1 Panorama of the Center of the Orion Nebula

A cavern of gas and dust in the nebula contains 700 young stars in various stages of formation.

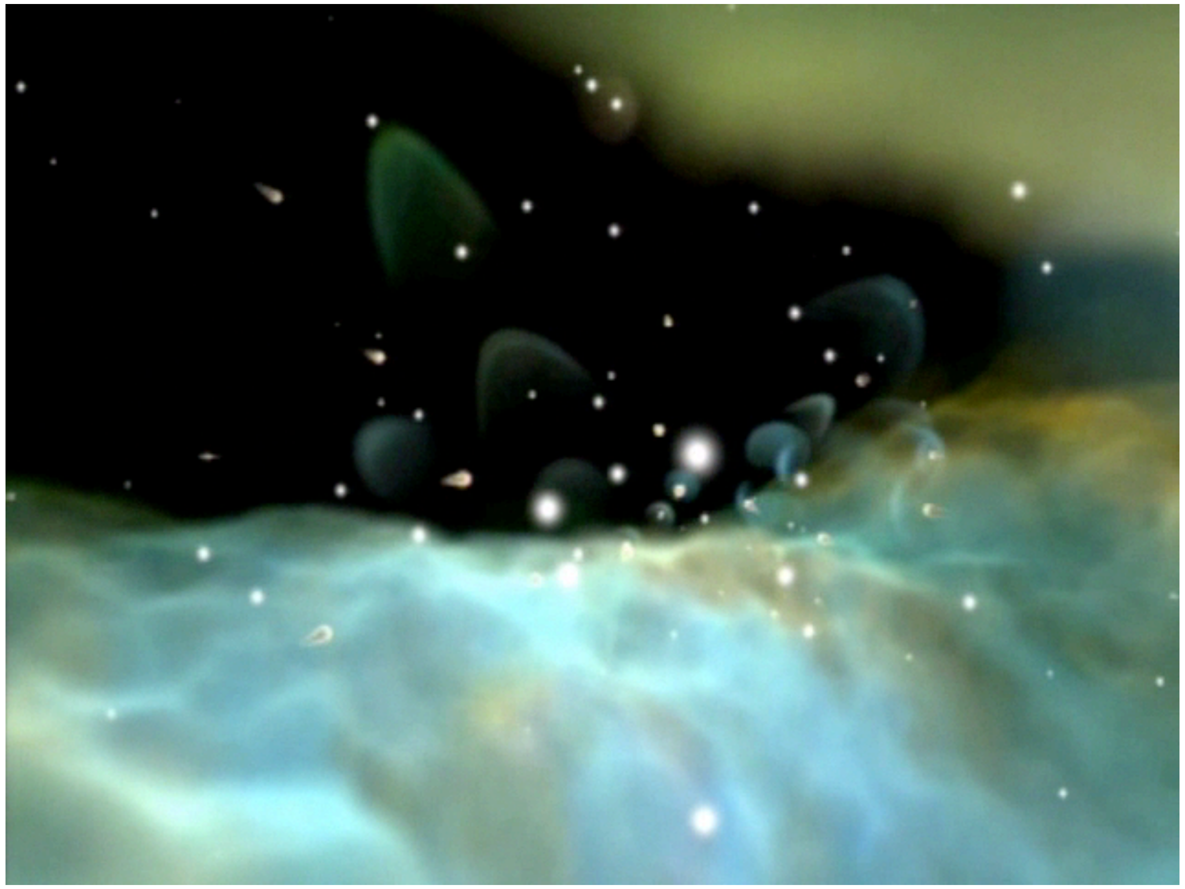
Astronomers once thought that the disks of dust around stars that coalesce into solar systems, called protoplanetary disks, would be impossible to see. The disks were hidden inside larger clouds of gas and dust, making them difficult to discern.

Hubble torpedoed this idea, finding numerous protoplanetary disks by identifying the dark clots of dense dust against the bright background of glowing nebulae. Hubble's observations have shown that the environment in which a star develops influences its prospects for planet formation. Hubble observations have also given scientists clues about the missing steps in our knowledge of planet formation – for instance, just how a disk of gas and dust evolves into individual planetary bodies circling the newborn star.

Interactive 4.1 Embryonic Planetary Systems in the Orion Nebula

Get a closer look at young planetary systems in the making – disks of gas and dust which will one day give rise to new solar systems.

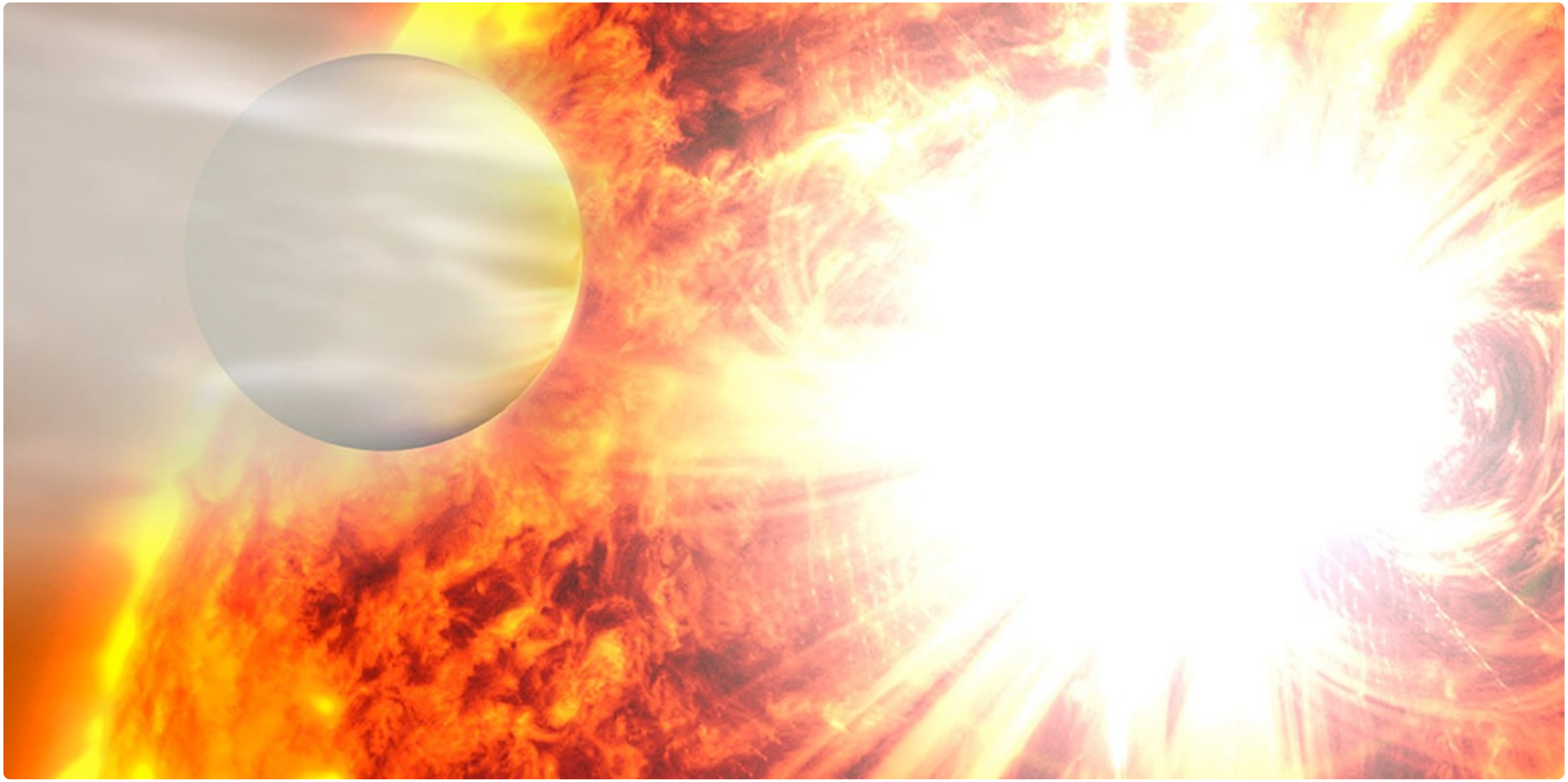
Movie 4.1 HubbleMinute: The First Steps of Planet Birth



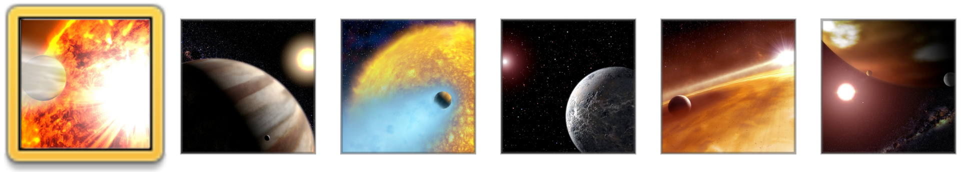
Scientists take a closer look at star formation in the Orion Nebula – and some of the puzzles involved.

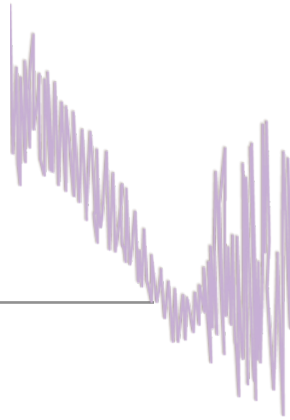
SECTION 2

Extrasolar Planets



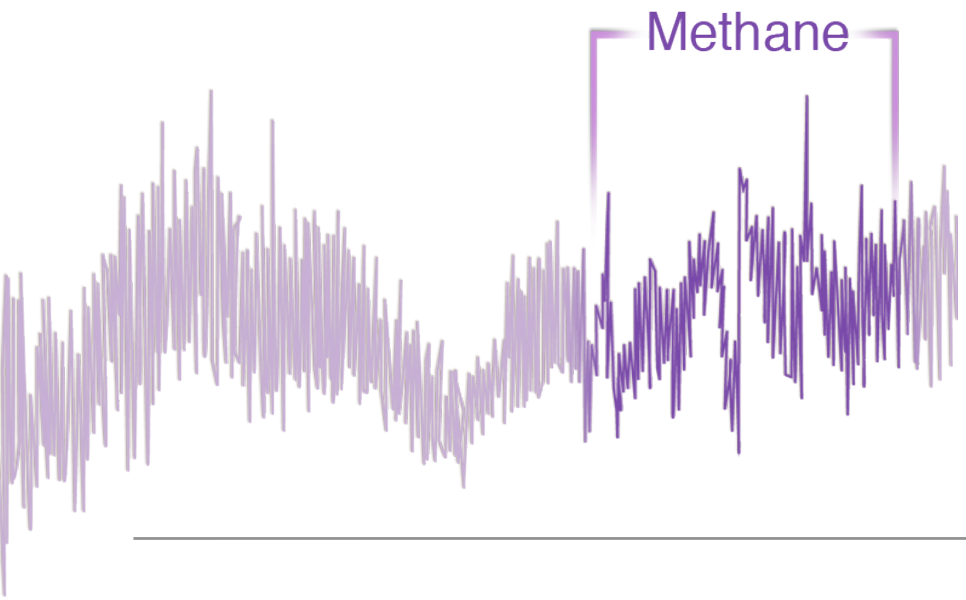
Evaporating atmosphere around exoplanet HD189733b (artist's rendering)





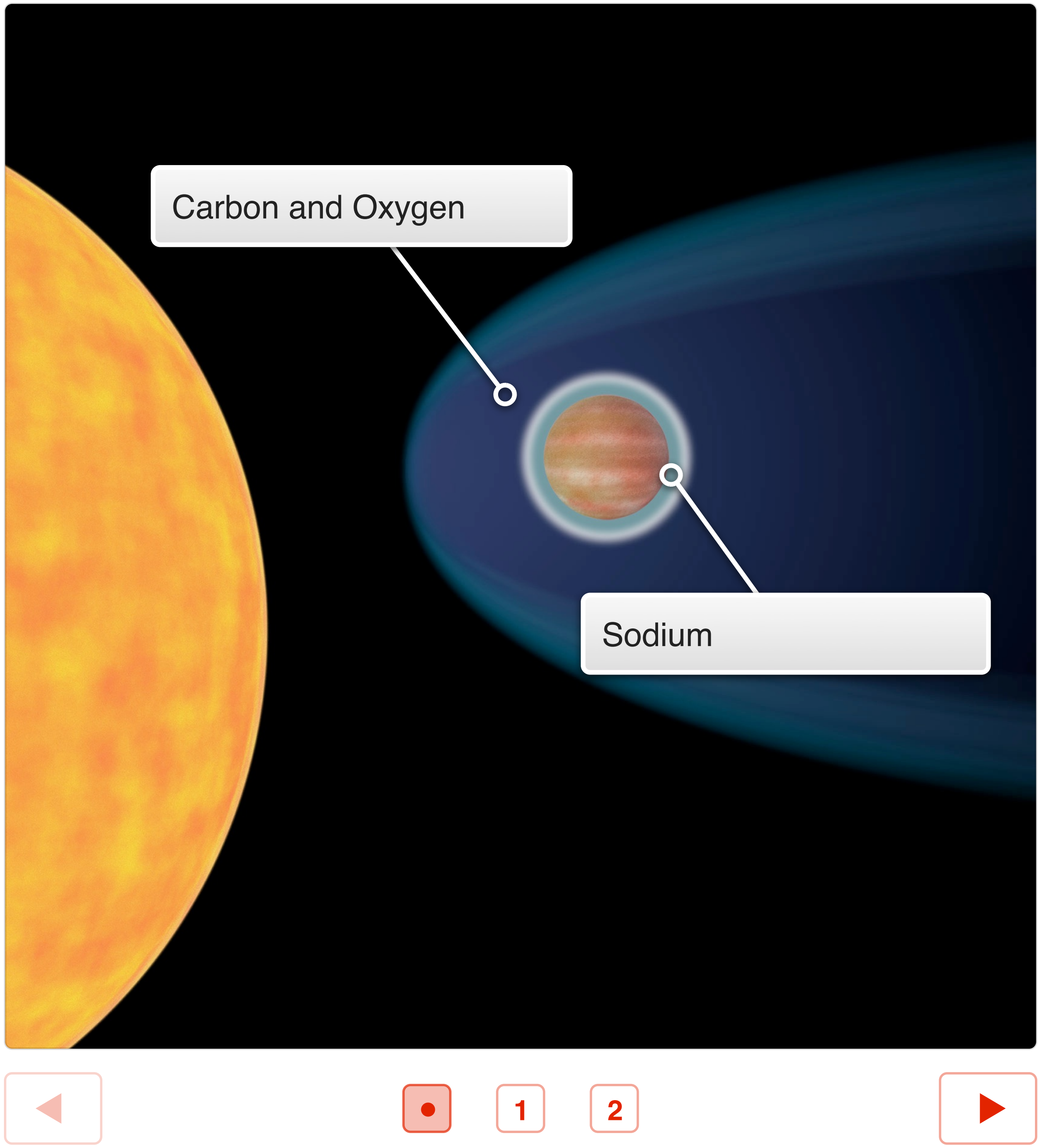
Hundreds of extrasolar planets have been discovered beyond our solar system. Most have been found by ground-based telescopes looking for tiny wobbles in the motion of a star as a planet tugs at it, or by the slight dimming of light as a planet passes in front of its parent star.

For the latter, Hubble can provide a more in-depth look, watching these light-blocking periods, called “transits,” for clues about the planets that cause them. Hubble also observes the light of the planet’s home star passing through the atmosphere of the planet, in a technique known as spectroscopy, and analyzes that light for information about the atmosphere’s composition. Thus far, Hubble has made some of the first measurements of the composition of planets around other stars, finding atmospheres containing sodium, carbon and oxygen, and a planet with a comet-like tail of hydrogen evaporating into space. It also found the first organic molecule on an extrasolar planet: methane in the atmosphere of a Jupiter-sized planet blisteringly close to its



Interactive 4.2 Hubble Measures the Atmospheric Structure of an Extrasolar Planet

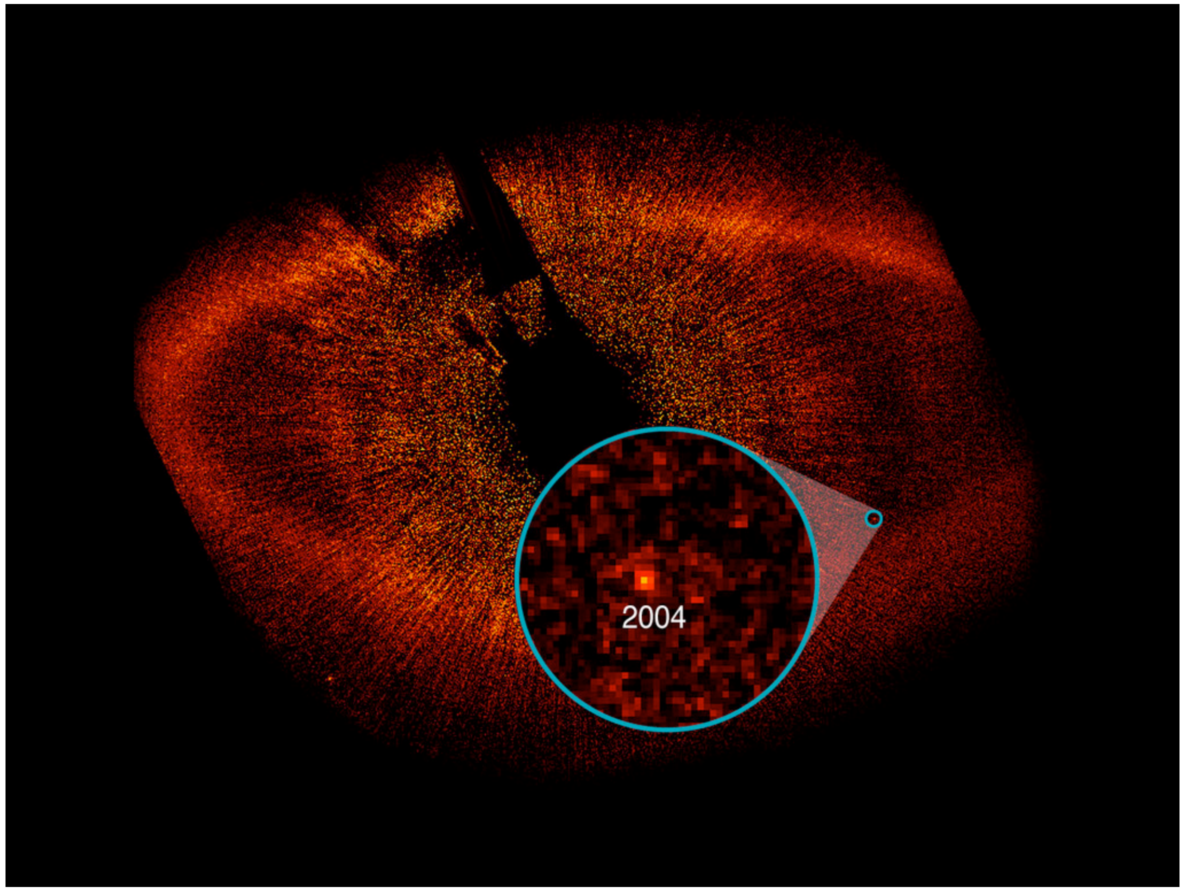
HD 209458b is too close to its star for Hubble to photograph directly. However, astronomers can observe the planet during transits across the star. Light passing through the atmosphere around the planet is scattered and acquires a signature from the atmosphere.



star. Hubble's ability to make these observations was a breakthrough, confirming and bolstering the idea that space telescopes could analyze the atmospheres of far-flung planets, and paving the way for current and future space telescopes that could carry on this science into the future.

Hubble also did what astronomers thought might not be possible: Take the first visible-light picture of a planet.

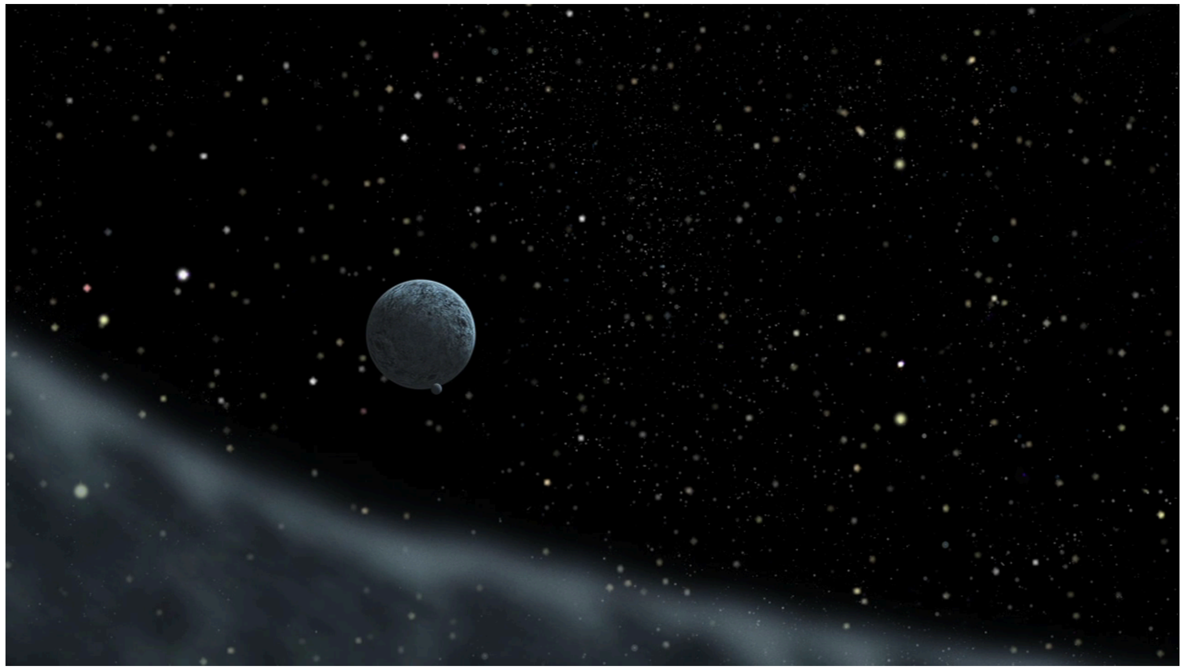
Interactive 4.3 **Hubble Observations of Planet Fomalhaut b**



Astronomers used coronographs to black out nearby light sources, such as the star in the center of this image, in order to see the much dimmer planet as it passes near the dust ring around the star. Images taken years apart show the planet moving along its expected orbit.

Astronomers had suspected since the early 1980s that the star Fomalhaut might have planets, based on observations of its dusty surroundings. In a Hubble image of the dust belt around a star, a tiny speck is planet Fomalhaut b: a world approximately three times the size of Jupiter and possibly surrounded by a bright disk of gas and dust.

Movie 4.2 **Hubble Sees a Planet Circling Another Star for the First Time**



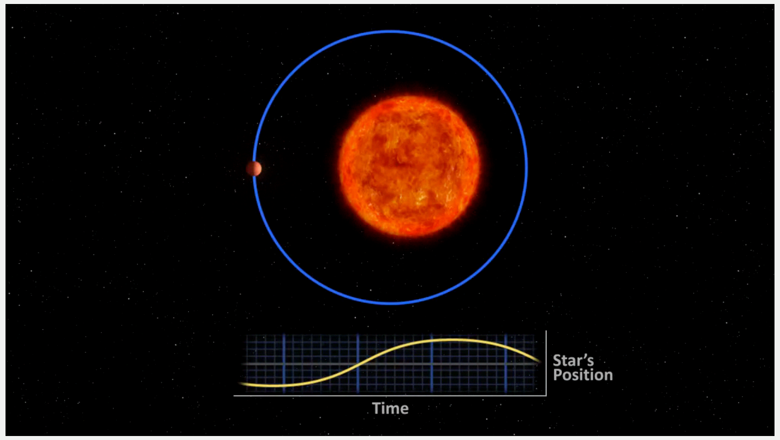
After years of suspecting the existence of planets in other solar systems in the universe, the Hubble Space Telescope captures visible-light images that, for the first time, provide concrete evidence of these extrasolar planets. A scientist explains the discovery of Fomalhaut b, the first extrasolar planet captured on camera in visible light.

Planet-Hunting Techniques

Planets are tiny relative to most other objects in the universe. And they can be a billion times dimmer than the stars they orbit.

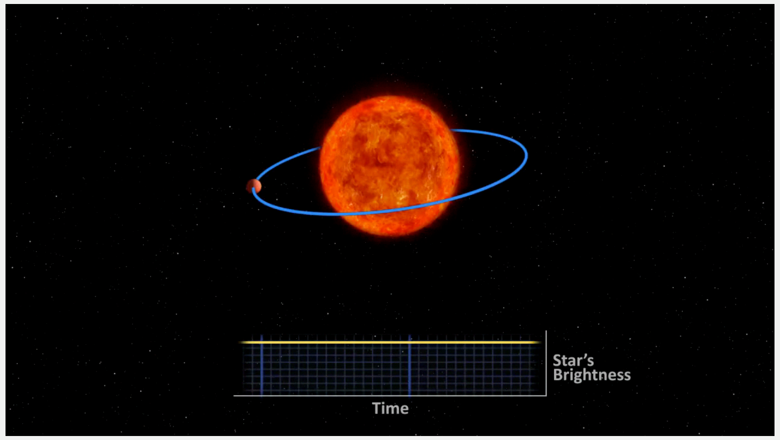
Because planets in other solar systems are nearly impossible to see directly, astronomers have had to come up with innovative ways to hunt these covert objects. Here are several movies demonstrating techniques used to find extrasolar planets.

Movie 4.3 Hunting via Astrometry



The gravity of a planet pulls its parent star just a little out of place as the planet orbits. Sometimes a telescope with exceptionally sharp vision can see the star moving back and forth in the sky. If the star sways with a periodic rhythm, a planet may be pulling at it.

Movie 4.4 Hunting via Transit Method

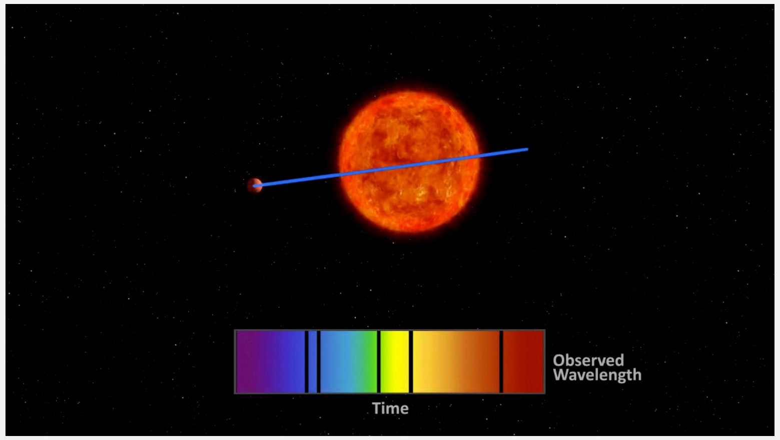


Planets that pass in front of their parent stars from our viewpoint will cause the star to dim just slightly as they block some of the light. Astronomers monitor stars for these telltale changes in brightness.

Movie 4.5 Hunting via Direct Imaging

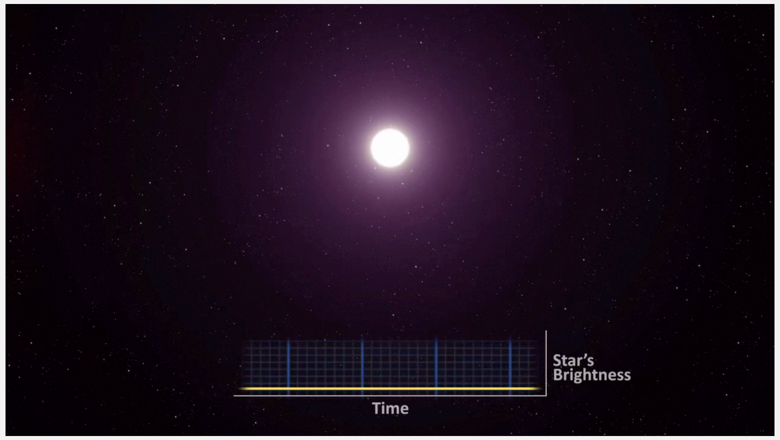
Because stars are so bright and planets so dim, it's difficult to take a direct picture of an extrasolar planet. But a dark "mask" called a coronograph can sometimes block enough of the star's light to pick up the dimmer, reflected light of the orbiting planet.

Movie 4.6 Hunting via Radial Velocity



A planet's gravity causes its star to wobble. Telescopes detect this wobble by studying the starlight, broken into a spectrum of colors. Dark lines caused by light being absorbed by the star's atmosphere shift as the star wobbles.

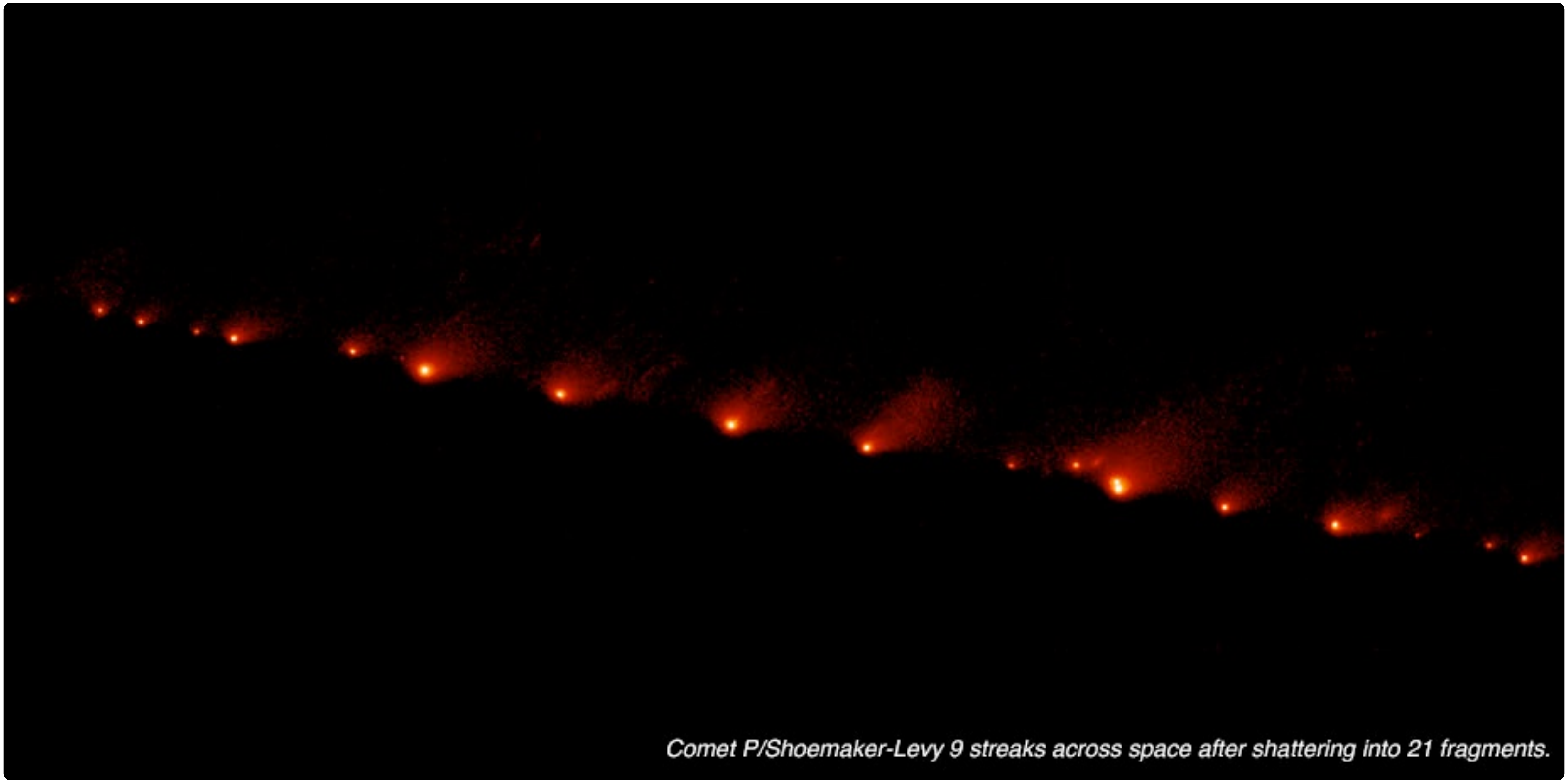
Movie 4.7 Gravitational Microlensing



When one celestial object passes in front of another, its gravity can bend and magnify the light of the object behind it, causing it to brighten. If the closer star has a planet, the farther star will brighten twice.

SECTION 3

Solar System Comet Crashes



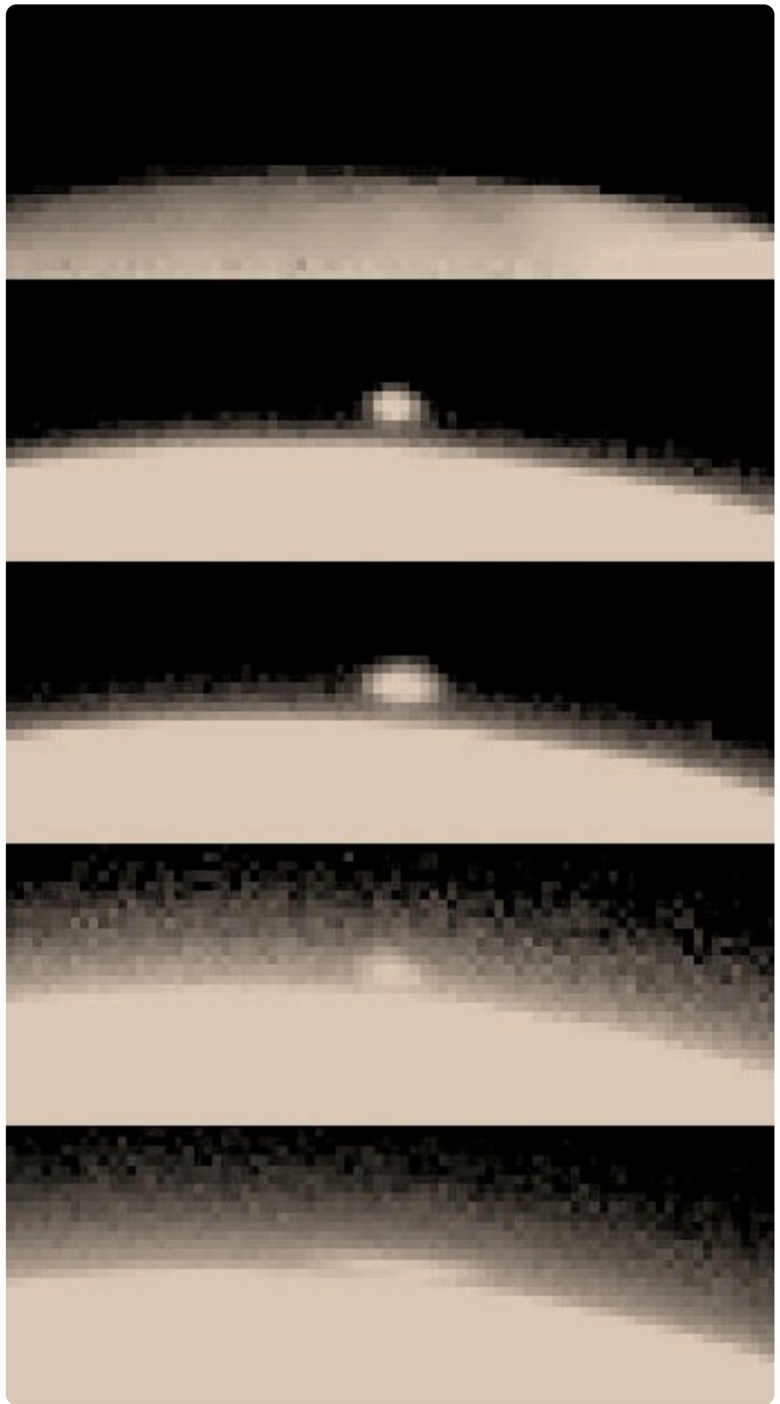
Comet P/Shoemaker-Levy 9 streaks across space after shattering into 21 fragments.

In 1994, Comet Shoemaker-Levy 9 plunged into the atmosphere of Jupiter, sending great plumes of debris blossoming from the planet. Hubble had a spectacular view of the event, monitoring the comet as it approached the collision. It observed the comet, which had been shattered into dozens of fragments by Jupiter's gravity, and watched as

Movie 4.8 **Comet P/Shoemaker-Levy 9 Hits Jupiter**

This visualization shows the major fragments of comet P/Shoemaker-Levy 9 colliding with Jupiter. The impacts occurred over a series of about six Earth days. (One animated second = 10 hours.)

Figure 4.2 **First Strike (1994)**

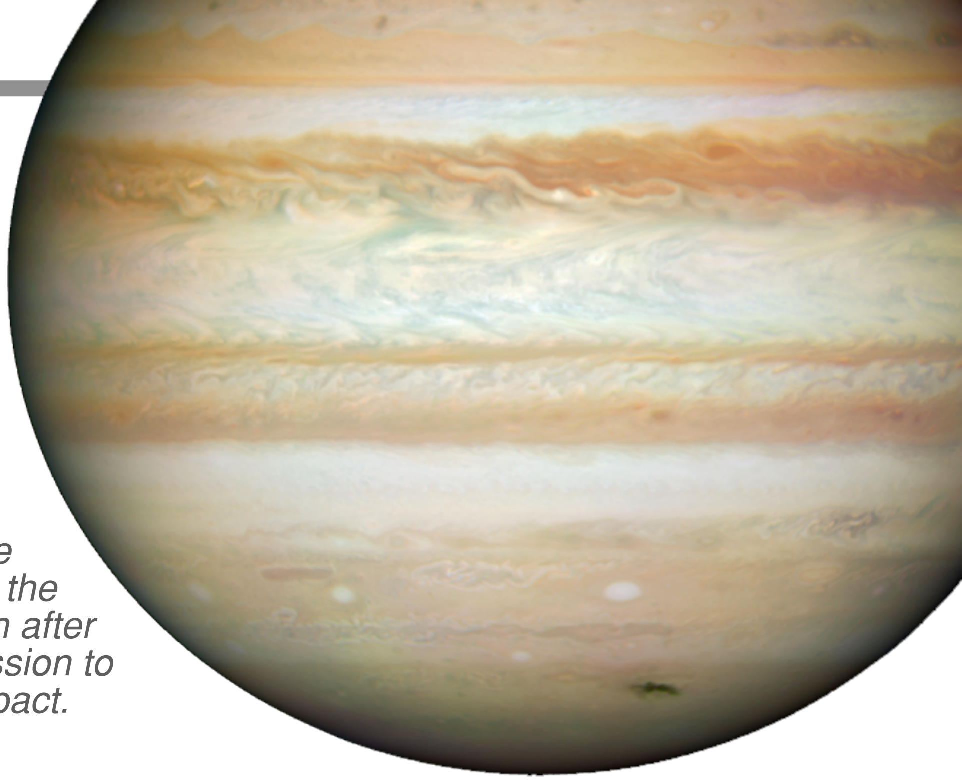


This image sequence shows a plume near Jupiter's limb at the time of the first comet P/Shoemaker-Levy 9's fragment impact.

violent waves rippled away from the impact sites. It was a once-in-a-thousand-years-event – or so scientists thought.

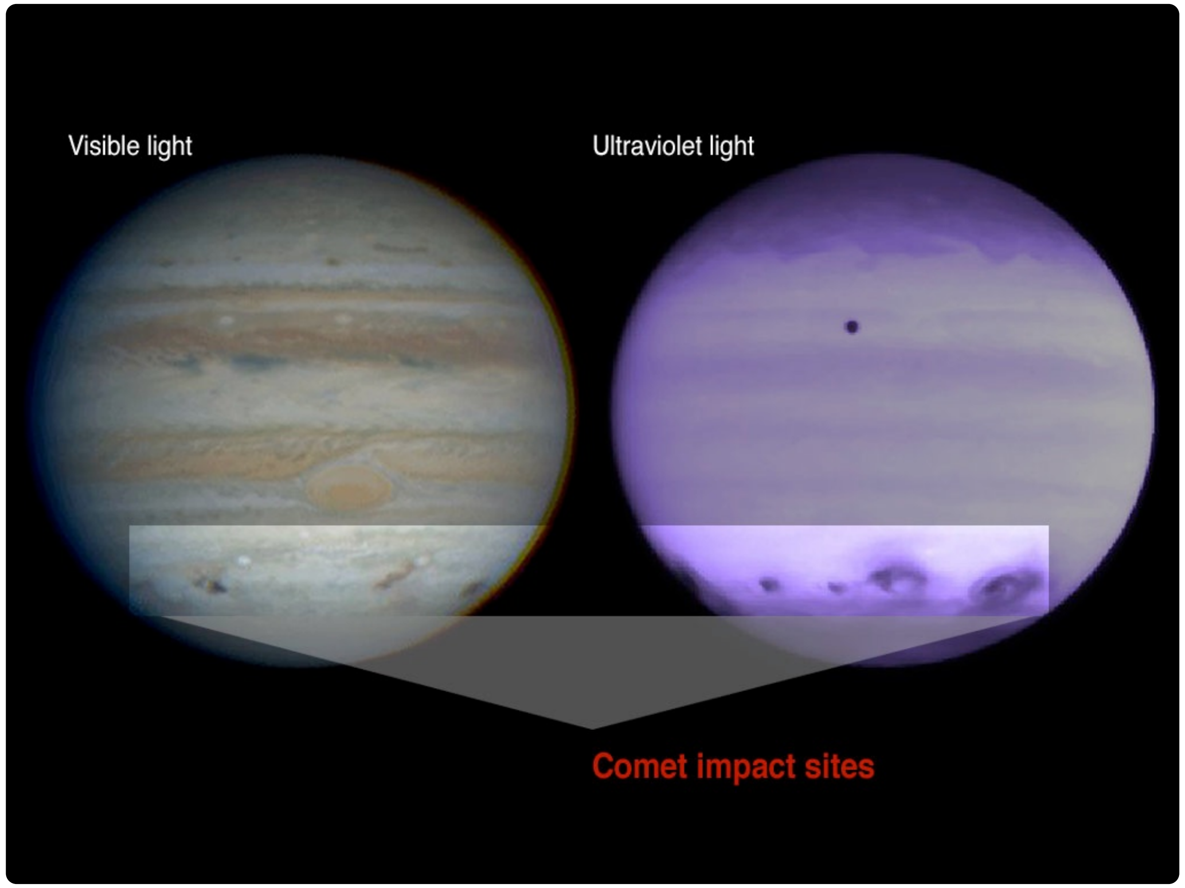
In May 2009, astronauts visited Hubble to install new instruments and make upgrades. In July, while engineers and scientists were still in the process of testing and adjusting the refurbished telescope, an amateur astronomer discovered a strange dark spot bruising Jupiter's surface. The giant planet had been struck again. An asteroid had streaked unnoticed into the planet, leaving an expanding impact site in its wake.

The Hubble team temporarily set aside its schedule to take pictures of the impact site with one of its new instruments. The rare event was too important to miss.



In July 2009, an asteroid struck Jupiter, leaving a bruise the size of the Pacific Ocean. Hubble engineers interrupted the telescope's calibration after a recent servicing mission to snap a shot of the impact.

Figure 4.3 **Comet Impacts in Visible and Ultraviolet Light**



Hubble observes different forms of light, allowing us to see more detail than we otherwise would. An image of Jupiter as seen in visible light (left) shows impact sites in the southern hemisphere. An image of the planet taken 20 minutes later in ultraviolet light (right), shows the same sites. But because the fine particles are easier to see in ultraviolet light, this image gives us a clearer picture of the comet residue and of materials thrown from Jupiter's lower atmosphere into the upper by the impact. Both images were taken on July 17, 1994.

Hubble's images of Jupiter's impact sites raise questions about the composition of the planet. For instance, the properties of the waves racing outward from the Shoemaker-Levy 9 sites indicate that the planet's composition is less similar to that of the Sun than scientists previously believed. One of Hubble's advantages is its ability to take high-quality images of such events on short notice, providing observations that deepen our understanding of our cosmic neighborhood.

The brief interval between the impacts provokes the question of whether these events are as rare as previously thought. Scientists thought impacts in our solar system happen thousands of years apart. The timing of these incidents might be coincidental, or it could mean collisions happen more frequently than we suspect.

CHAPTER 5

The Space Telescope

Hubble's final release over Earth (2009)

The Space Telescope

Since the earliest days of astronomy astronomers have shared a single goal – to see more, see farther, see deeper. The Hubble Space Telescope’s launch in 1990 sped humanity to one of its greatest advances in that journey.

Hubble is one of NASA’s most successful and long-lasting science missions. Its position above the atmosphere gives it a view of the universe that typically far surpasses that of ground-based telescopes. It has beamed hundreds of thousands of images back to Earth, shedding light on many of the great mysteries of astronomy.

Interactive 5.1 3D Model of the Hubble Space Telescope

The Legend Behind the Name

The Hubble Space Telescope was named after astronomer Dr. Edwin Powell Hubble, who made some of the most important discoveries in modern astronomy.

In the 1920s, while working at the Mt. Wilson Observatory with the most advanced technology of the time, Hubble showed that some of the numerous distant, faint clouds of light in the universe were actually entire galaxies – much like our own Milky Way. The realization that the Milky Way is only one of many galaxies forever changed the way astronomers viewed our place in the universe.

Figure 5.1 **Edwin Hubble (1889–1953)**

But perhaps his greatest discovery came in 1929, when Hubble determined that the farther a galaxy is from Earth, the faster it appears to move away. This notion of an "expanding" universe formed the basis of the Big Bang theory, which states that the universe began with an intense burst of energy at a single moment in time – and has been expanding ever since.

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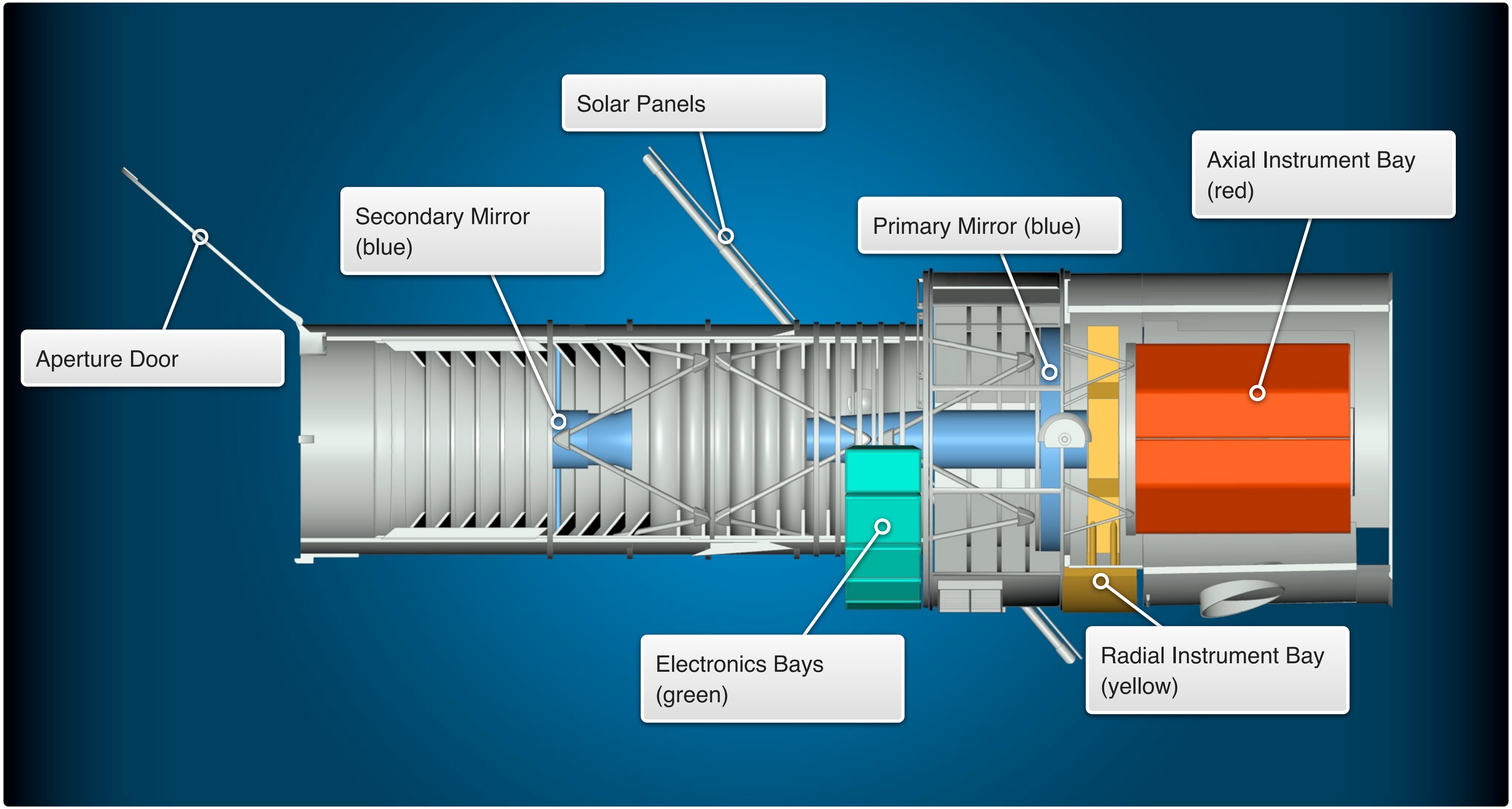
SECTION 1

How It Works



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Interactive 5.2 **A Cross-Section of the Hubble Space Telescope**

Hubble orbits Earth, moving at the speed of about five miles per second (8 km per second) – fast enough to travel across the United States in about 10 minutes. As it travels, Hubble's mirror captures light and directs it into its several science instruments.

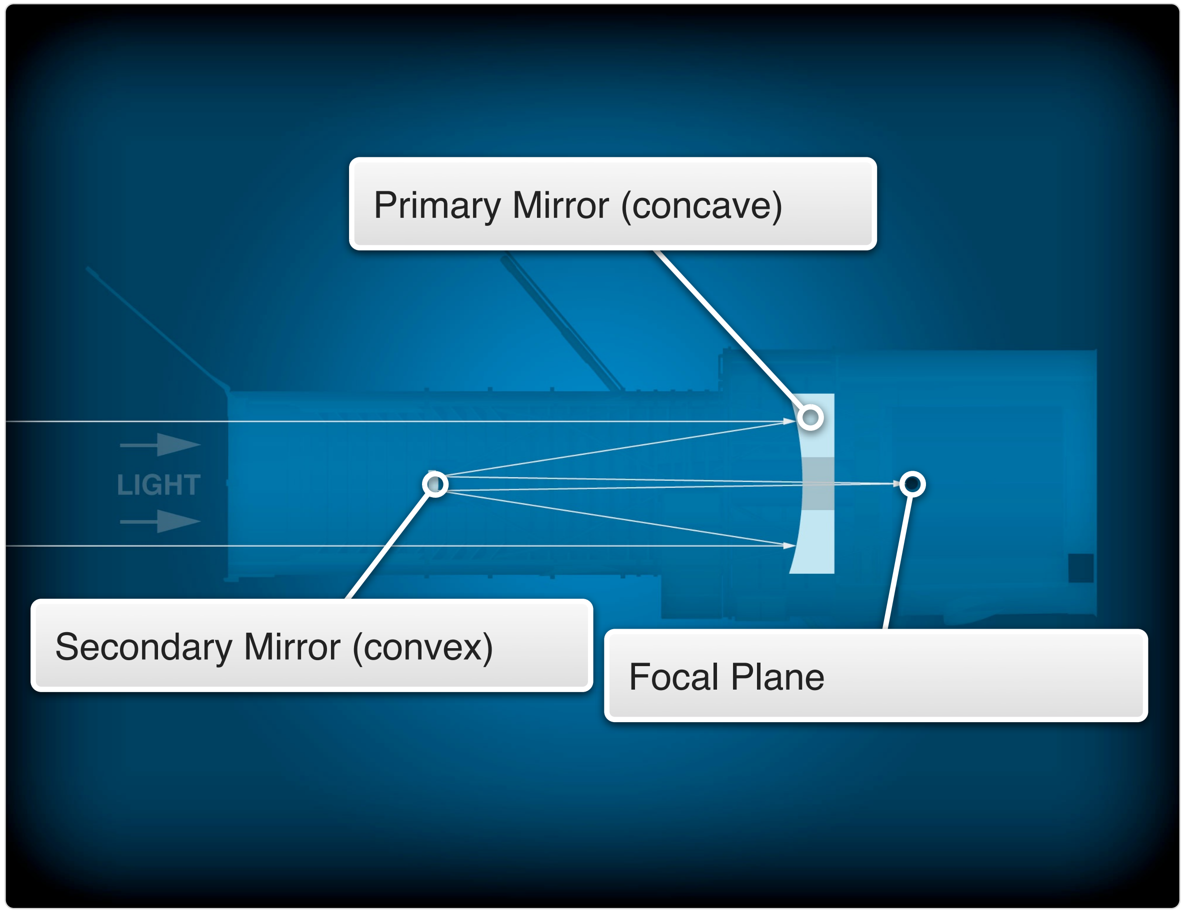
Hubble is a type of telescope known as a Cassegrain reflector. Light hits the telescope's main mirror, or primary mirror. It bounces off the primary mirror and encounters a secondary mirror. The secondary mirror focuses the light through a hole in the center of the primary mirror that leads to the telescope's science instruments.

People often mistakenly believe that a telescope's power lies in its ability to magnify objects. Telescopes actually work by collecting more light at higher resolution than the human eye can see. The larger a telescope's mirror, the more light it can collect, and the better its vision. Hubble's primary mirror is 94.5 inches (2.4 m) in diameter. This mirror is small compared with those of current ground-based telescopes, which can be 400 inches (1,000 cm) and up, but Hubble's location beyond the atmosphere gives it remarkable clarity.

Once the mirror captures the light, Hubble's science instruments work together or individually to provide the observation. Each instrument is designed to examine the universe in a different way.

All of Hubble's functions are powered by sunlight. Hubble sports solar arrays that convert sunlight directly into electricity. Some of that electricity is stored in batteries that keep the telescope running when it's in Earth's shadow, blocked from the Sun's rays.

Interactive 5.3 The Hubble Space Telescope's Design



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Current Instruments

Wide Field Camera 3 (WFC3) sees three different kinds of light: near-ultraviolet, visible and near-infrared, though not simultaneously. It is now the main and most efficient camera for Hubble's observations.

Cosmic Origins Spectrograph (COS) is a spectrograph that sees exclusively in ultraviolet light. Spectrographs, like prisms, separate light from the cosmos into its component colors. This provides a wavelength "fingerprint" of the object being observed, which tells us about its temperature, chemical composition, density, and motion.

Advanced Camera for Surveys (ACS) sees in wavelengths from the far ultraviolet to near-infrared light, and is designed to study some of the earliest activity in the universe. ACS helps map the distribution of dark matter, detects the most distant objects in the universe, searches for massive planets, and studies the evolution of clusters of galaxies.

Space Telescope Imaging Spectrograph (STIS) is a spectrograph that sees ultraviolet, visible and near-infrared light, and is known for its ability to hunt black holes. While COS works best with small sources of light, such as stars or quasars, STIS can map out larger objects like galaxies.

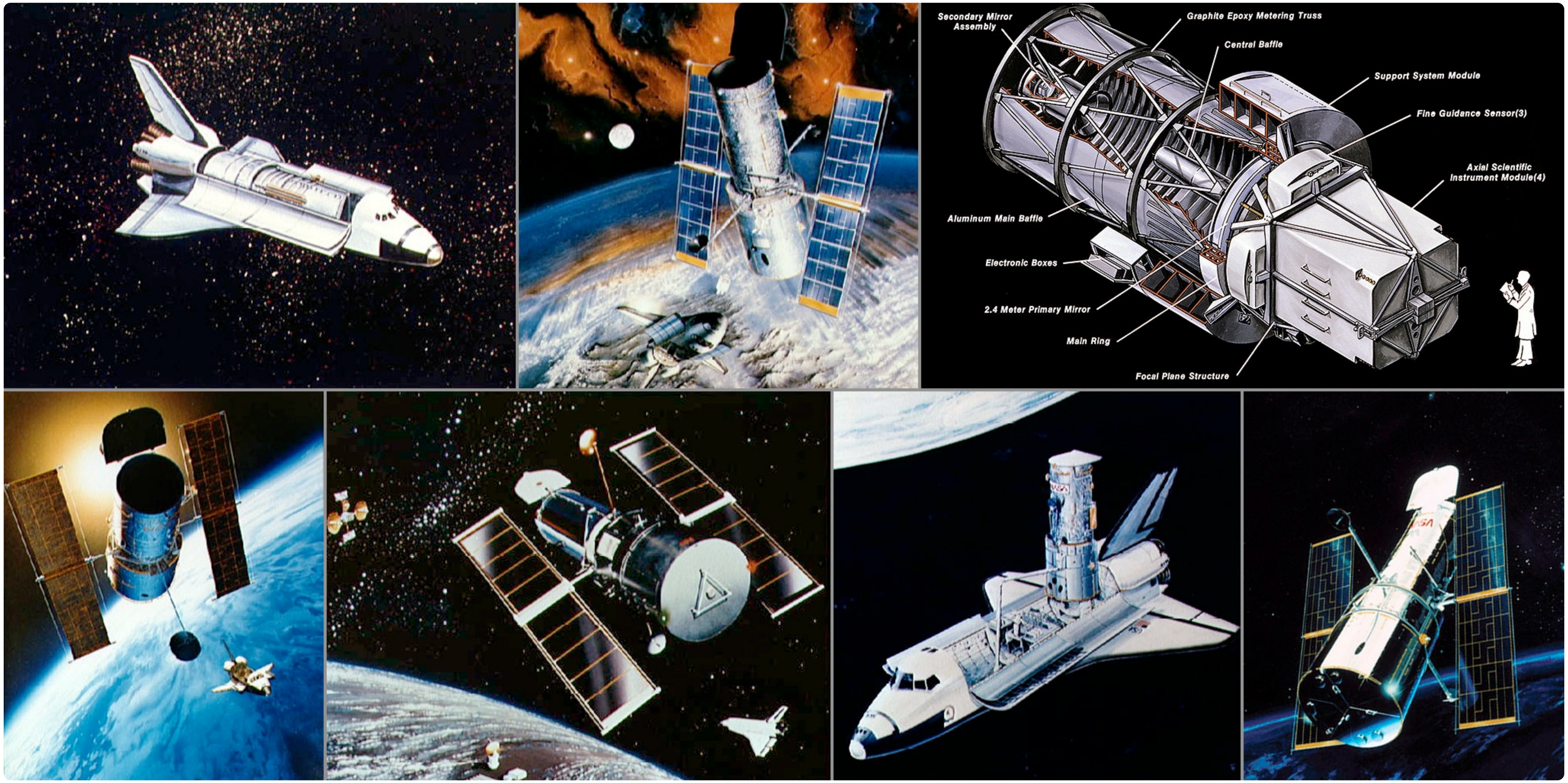
Gallery 5.1 Hubble's Instruments at Work

Hubble's primary camera, WFC3, imaged NGC 6302 in ultraviolet and visible light with a variety of filters to infer properties of the nebular gas.

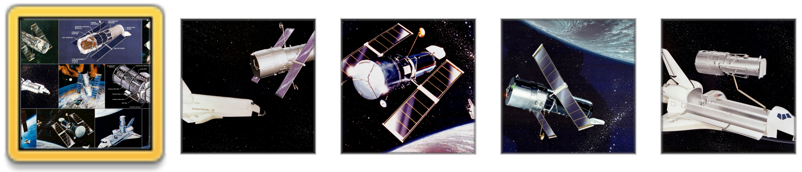
Near Infrared Camera and Multi-Object Spectrometer (NICMOS) is Hubble's heat sensor. Its sensitivity to infrared light – perceived by humans as heat – lets it observe objects hidden by interstellar dust, like stellar birth sites, and gaze into deepest space.

The Fine Guidance Sensors (FGS) are devices that lock onto "guide stars" and keep Hubble pointed in the right

First Thoughts



Gallery 5.2 Early Concept Art for the Large Space Telescope Project

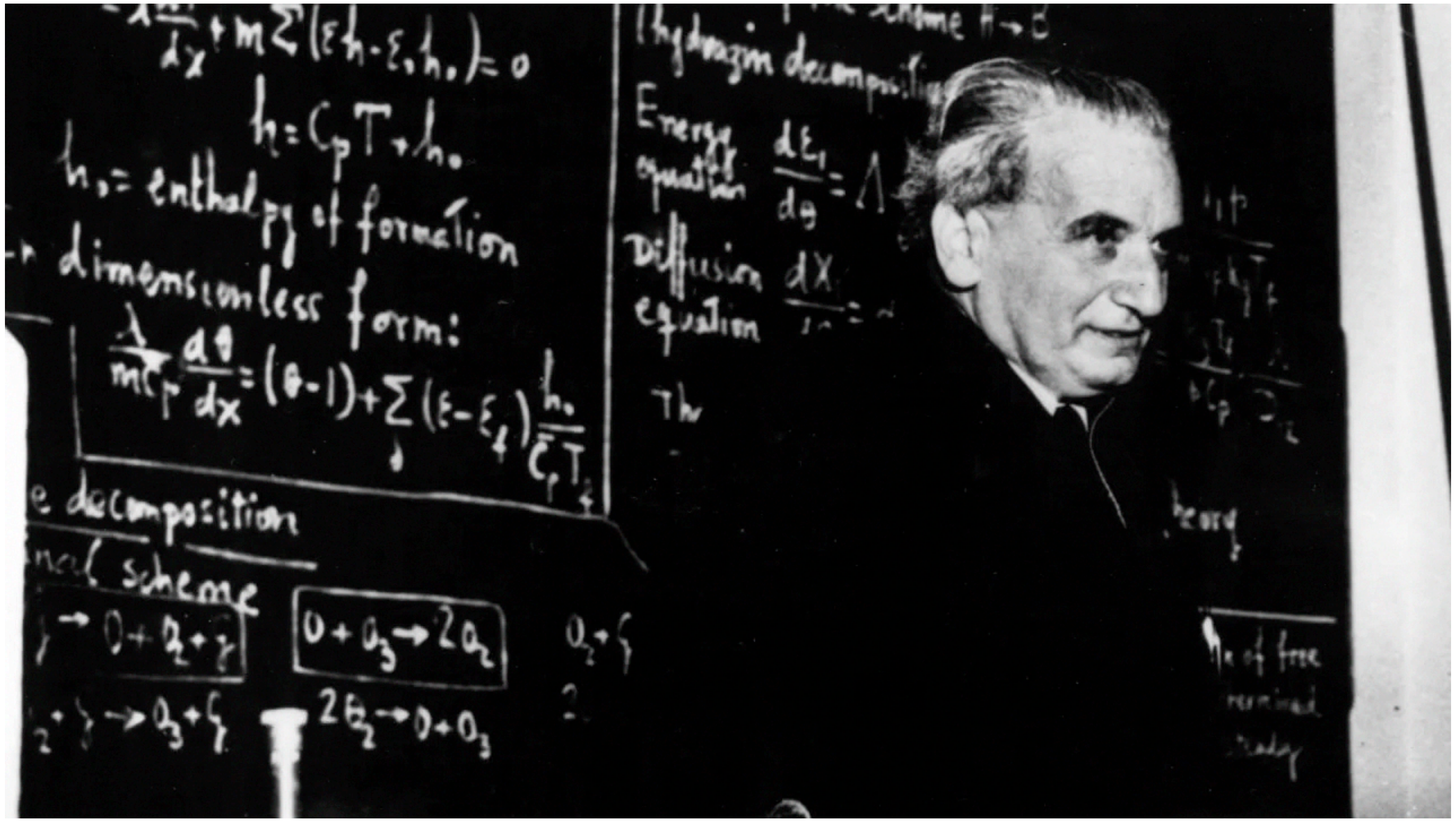


The idea for a space telescope arose in 1923, when German scientist Hermann Oberth, one of the founders of rocketry, suggested blasting a telescope into space aboard a rocket. In 1946, Lyman Spitzer Jr., an American astrophysicist, wrote a paper proposing a space observatory. He would spend the next 50 years working to make that space telescope a reality.

NASA approved what was then called the Large Space Telescope Project in 1969. Because of budget considerations, the original proposal was downsized, decreasing the size of the telescope's mirror and the number of instruments it would carry.

The group working on the project suggested a telescope with a number of interchangeable instruments. The Space Shuttle would be used to put the telescope in orbit and either return it to Earth for repairs and replacement instruments, or service it in space.

Movie 5.1 The Stuff of Legend

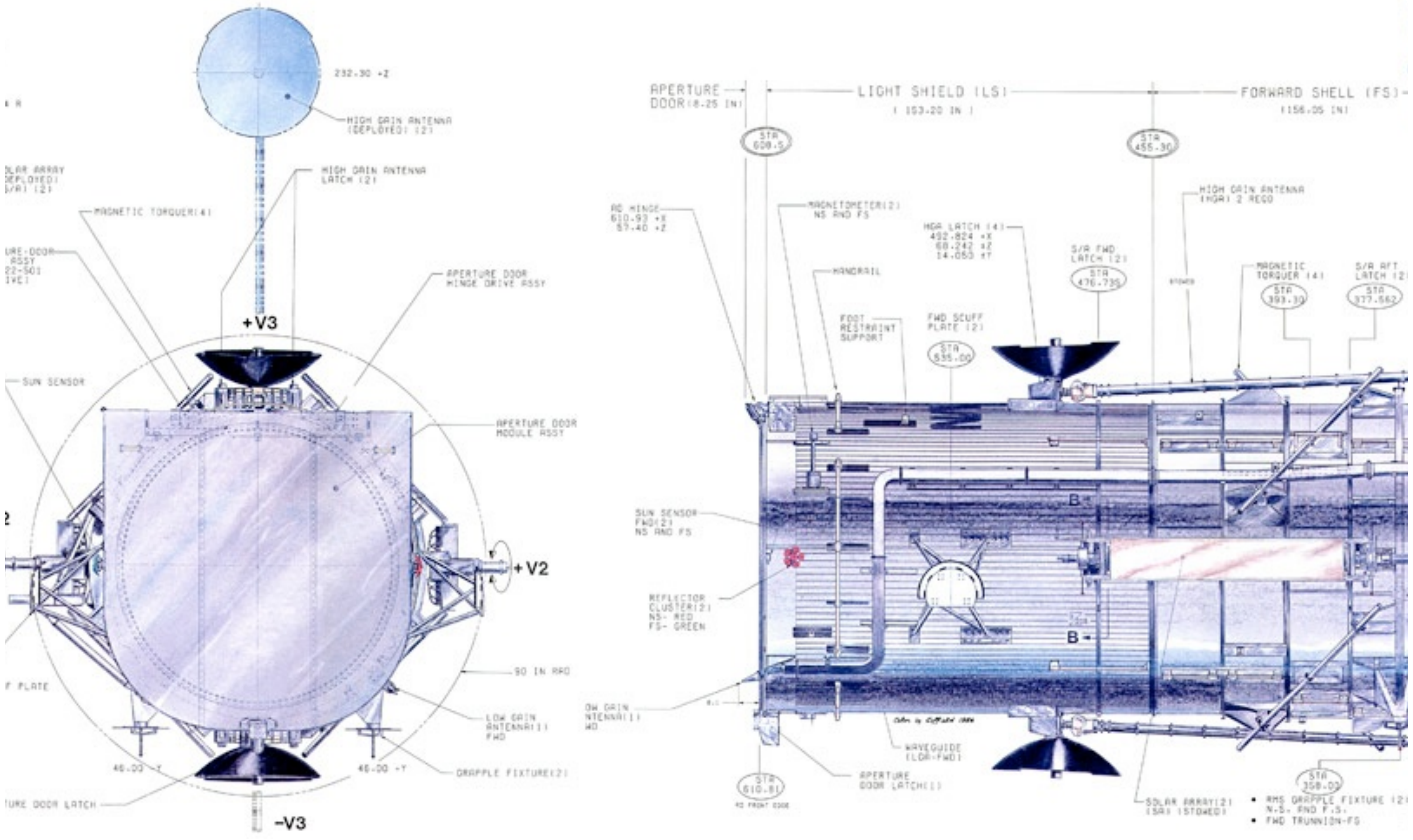


Decades before the Hubble Telescope was a reality, legendary scientists considered the possibility of a space observatory.

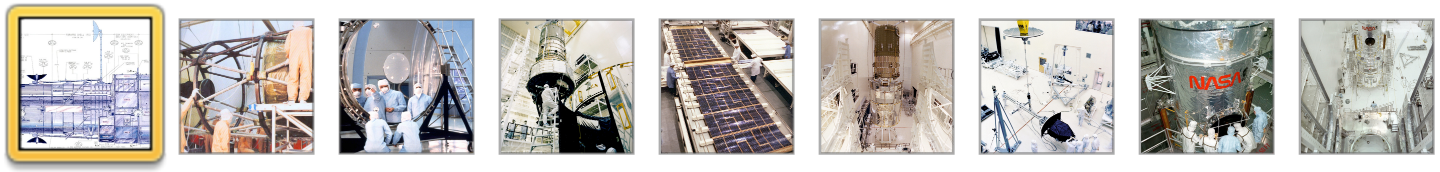
In 1975, the European Space Agency (ESA) began to work together with NASA on a plan that would eventually become the Hubble Space Telescope. ESA's support was critical, granting NASA an international partner that could supply both manpower and funding. ESA would provide both the solar cells and one of the telescope's instruments – the Faint Object Camera. Reassured by the partnership, Congress approved funding for the telescope in 1977.

Work began, with NASA centers and companies like Lockheed Missiles and the Perkin-Elmer Corporation steadily transforming the vision of the Hubble Telescope into reality, piece by piece. By 1979, astronauts were training for the mission in an underwater tank to simulate weightlessness, using a telescope mock-up.

Gallery 5.3 Constructing the Hubble Space Telescope

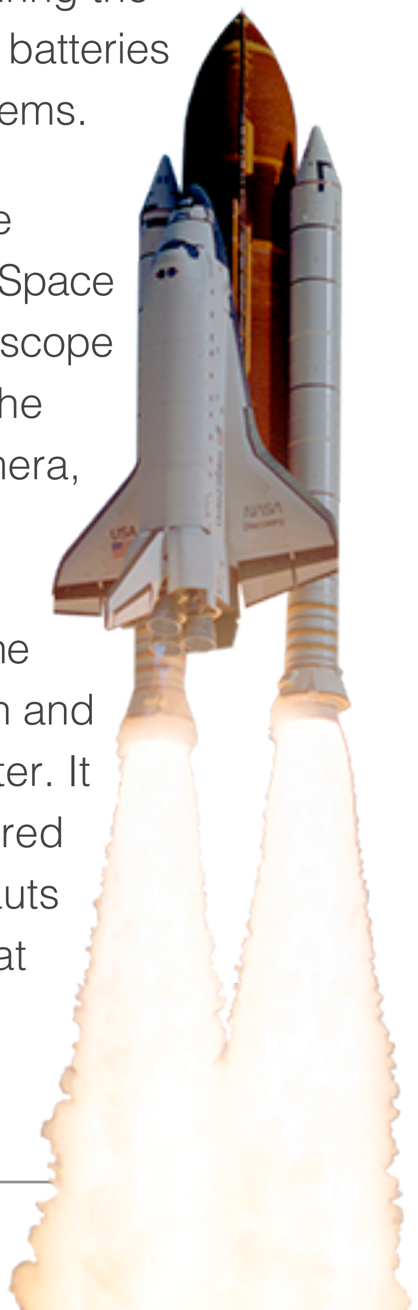


The Lockheed Missiles and Space Company (Lockheed Martin) diagram of the Hubble Space Telescope (1981).

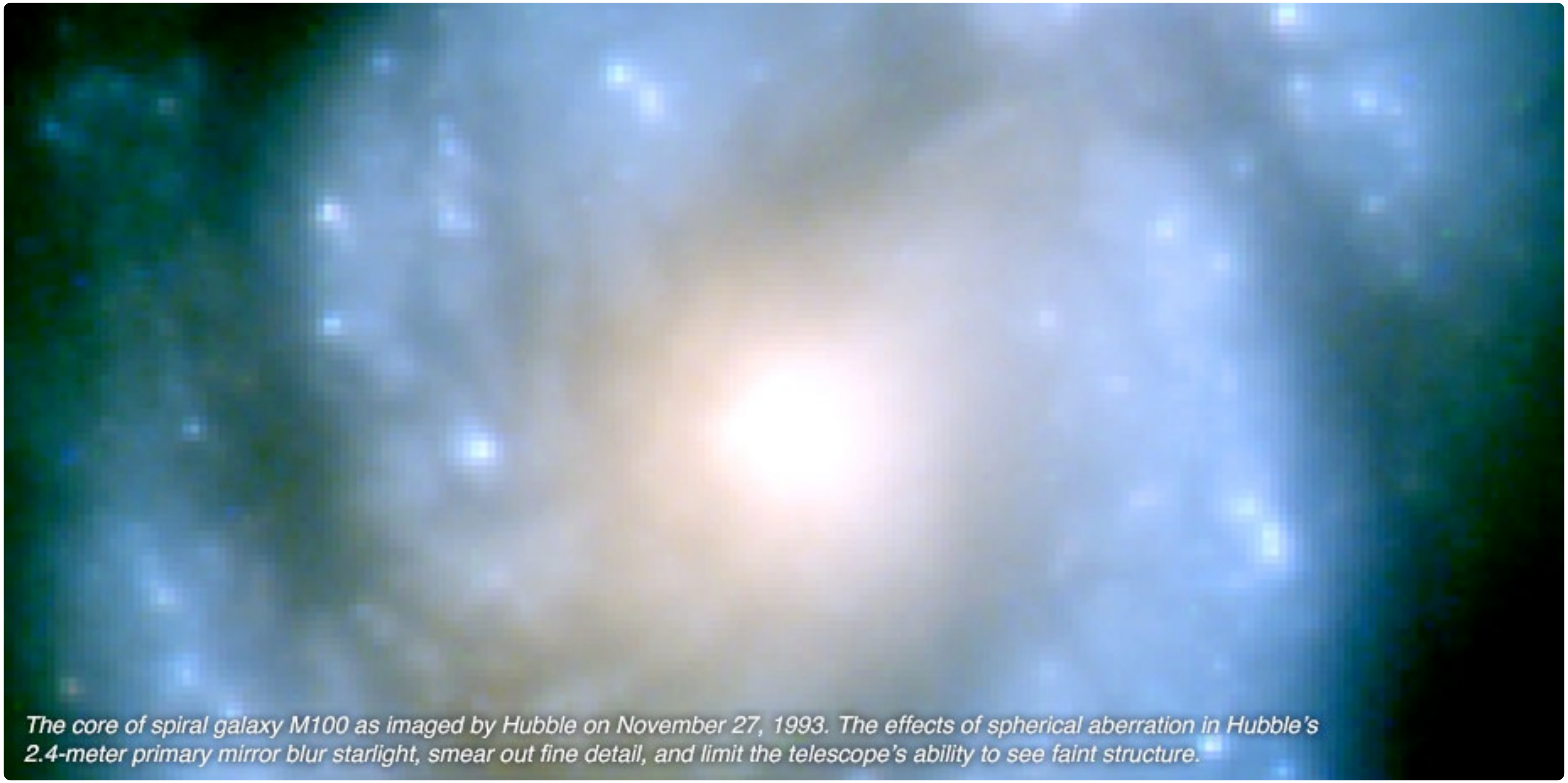


After some delays, Hubble's launch was scheduled for October 1986. But on January 28, 1986, tragedy struck. The Space Shuttle Challenger exploded just over a minute into its flight. Shuttle flights ceased for two years. The finished telescope parts were moved into storage. Hubble workers continued to tweak the telescope during the delay, improving the solar batteries and upgrading other systems.

On April 24, 1990, Hubble launched into orbit aboard Space Shuttle Discovery. The telescope carried five instruments: the Wide Field/Planetary Camera, the Goddard High Resolution Spectrograph, the Faint Object Camera, the Faint Object Spectrograph and the High Speed Photometer. It was designed to be repaired and upgraded by astronauts in orbit – an innovation that would be needed sooner rather than later.



A Rocky Start



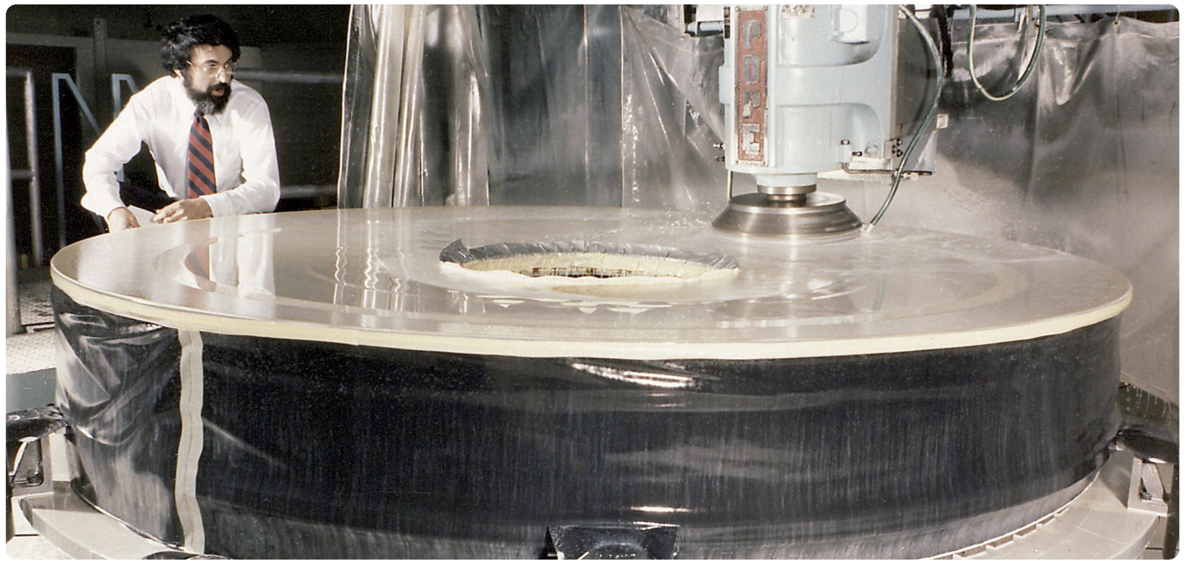
The core of spiral galaxy M100 as imaged by Hubble on November 27, 1993. The effects of spherical aberration in Hubble's 2.4-meter primary mirror blur starlight, smear out fine detail, and limit the telescope's ability to see faint structure.

Almost immediately after Hubble went into orbit, it became apparent that something was wrong. While the pictures were clearer than those of ground-based telescopes, they weren't the pristine images that had been promised. They were blurry.

Hubble’s primary mirror, polished so carefully over the course of a full year, had a flaw called “spherical aberration.” It was just slightly the wrong shape, causing the light that bounced off the center of the mirror to focus in a different place than the light bouncing off the edge. The tiny flaw – about 1/50th the thickness of a sheet of paper – was enough to distort the view.

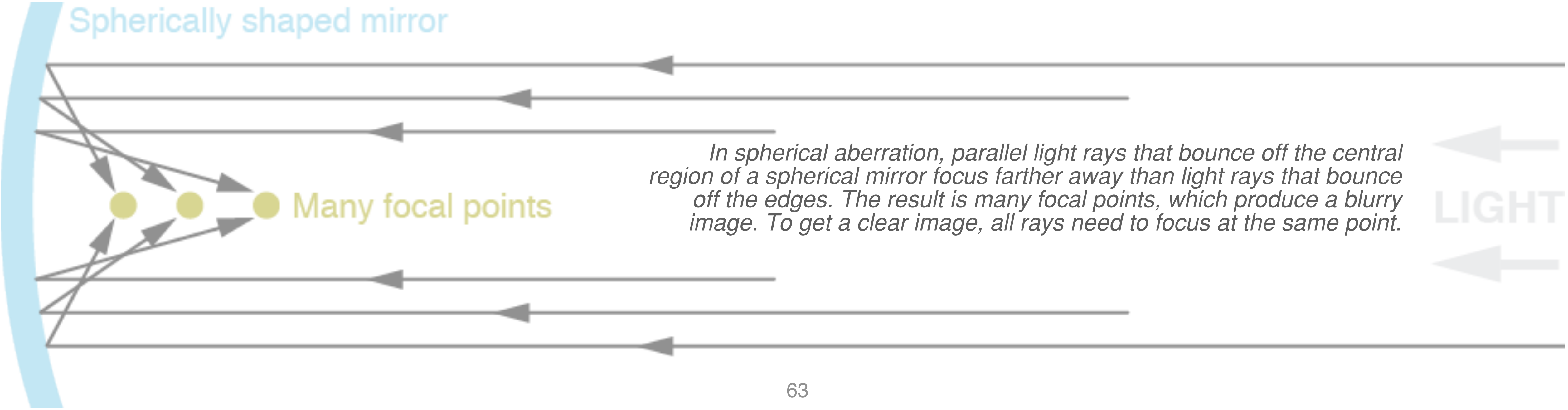
Fortunately, scientists and engineers were dealing with a well-understood problem – astronomers had been dealing with spherical aberration ever since the time of Galileo – but Hubble’s mirrors could not be altered or replaced while in orbit.

Figure 5.2 Grinding the Telescope’s Primary Mirror



Hubble’s primary mirror is seen being ground at the Perkin-Elmer Corporation's large optics fabrication facility.

A solution was found. A series of small mirrors could be used to intercept the light reflecting off the mirror, correct for the flaw, and bounce the light to the telescope’s science instruments. The Corrective Optics Space Telescope Axial Replacement, or COSTAR, could be installed in place of one of the telescope’s other instruments in order to correct the images produced by the remaining instruments. Astronauts would also replace the Wide Field/Planetary Camera with a



In spherical aberration, parallel light rays that bounce off the central region of a spherical mirror focus farther away than light rays that bounce off the edges. The result is many focal points, which produce a blurry image. To get a clear image, all rays need to focus at the same point.

new version, the Wide Field and Planetary Camera 2 (WFPC2), that contained small mirrors to correct for the aberration. This was the first of Hubble's instruments to have built-in corrective optics.

While scientists and engineers worked, Hubble beamed back images that, despite their flaws, still gave astronomers a closer look than they'd previously had at the kind of cosmic phenomena Hubble was intended to reveal. Scientists developed new image processing techniques to partially recover some of the information lost to the blurring. They watched a planet-spanning storm churn on Saturn. They saw a density of stars in galaxy M87 that helped reveal the scale of the supermassive black hole at its core. They observed the lobes of gas emitted by the unstable, explosive, supermassive star Eta Carinae. The science being accomplished with Hubble's problematic optics hinted at the still greater feats that could be performed with a fixed mirror.

Figure 5.3 **Major Storm on Saturn, 1990**

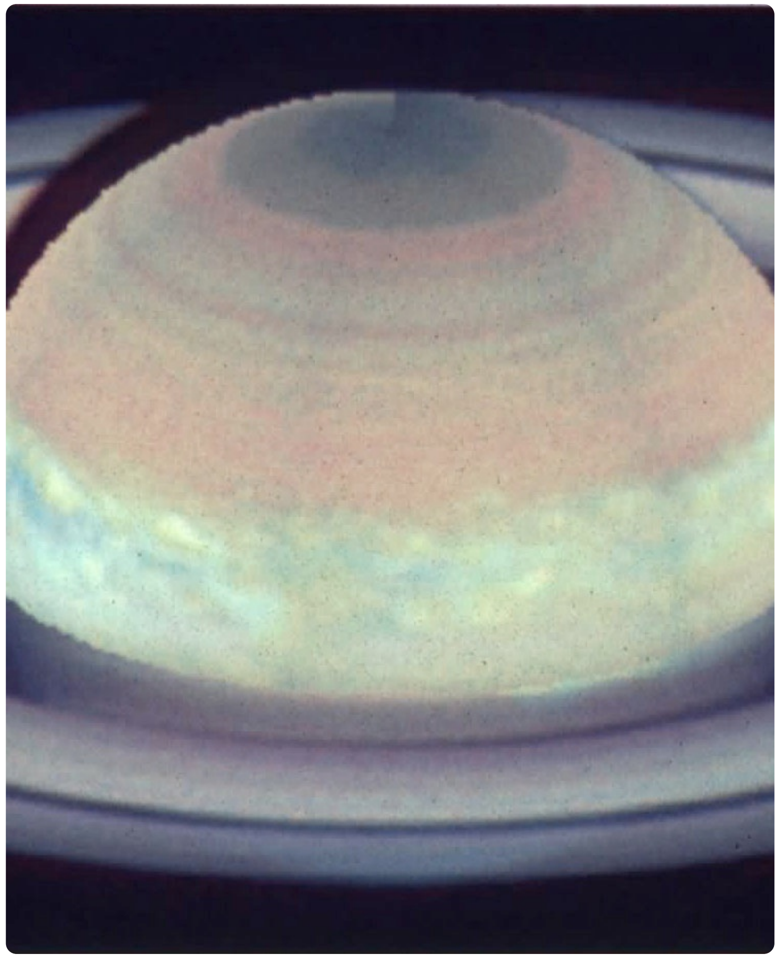
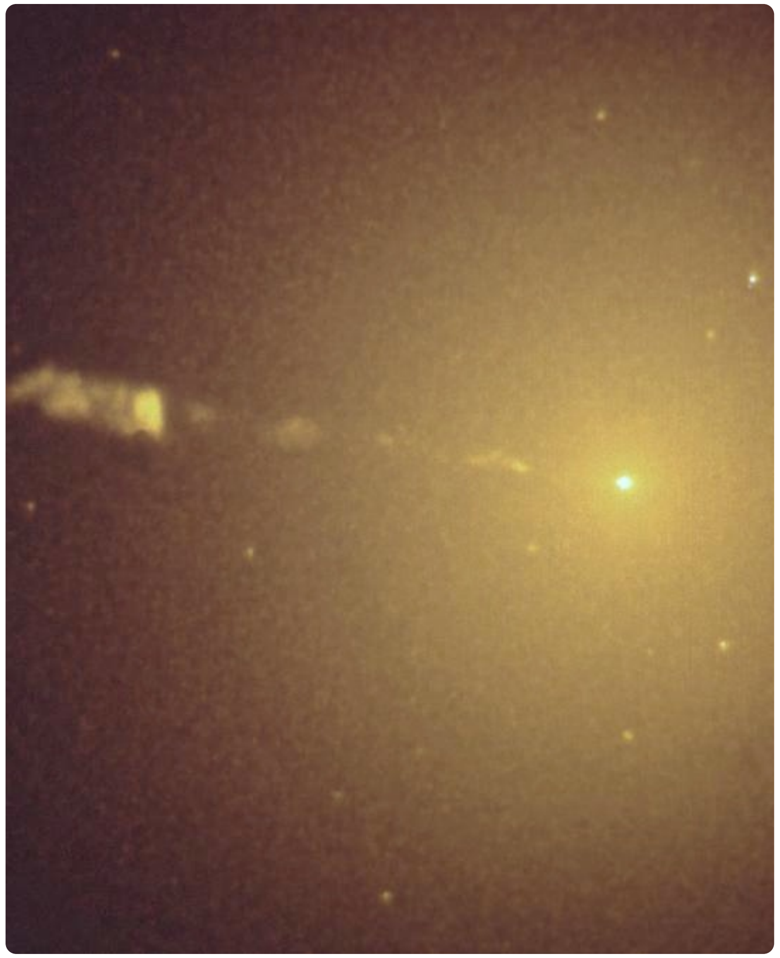


Figure 5.4 **Eruption of Eta Carinae, 1991**

Figure 5.5 **Nucleus of Galaxy M87, 1991**

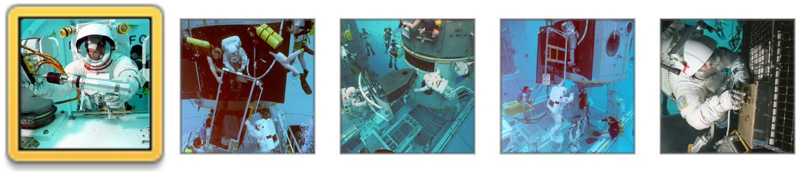


Astronauts and NASA staff spent 11 months training for one of the most complex space missions ever attempted. Over one hundred specially-designed tools would be utilized in the repair tasks. In addition to the critical nature of the mission, it would be the first test of the telescope's vaunted ability to be serviced and repaired in space.

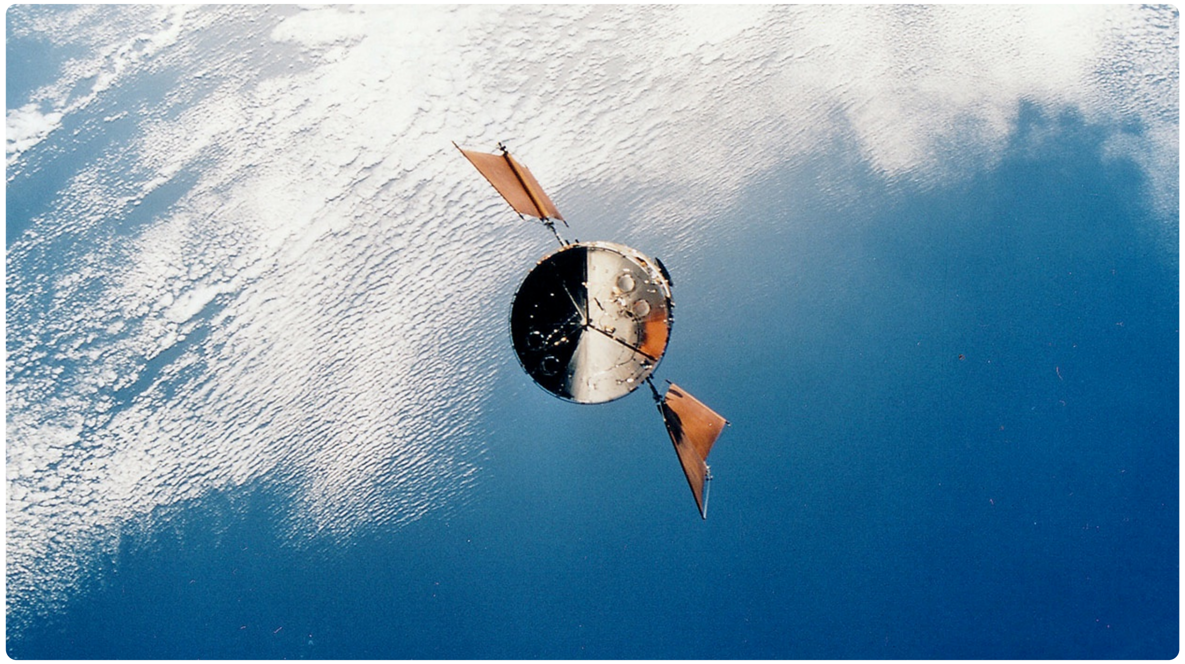
On December 2, 1993, the Space Shuttle Endeavor carried a crew of seven into orbit for a mission that would involve five days of spacewalks and repairs. They removed the High Speed Photometer and replaced it with COSTAR. They replaced the original Wide Field/Planetary Camera with the newer WFPC2. They performed a host of other tasks, replacing solar panels, fuse plugs, and other hardware. By December 9, they were finished.

Gallery 5.4 Astronauts Train for the First Servicing Mission

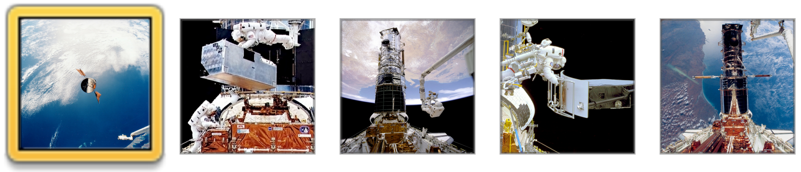
An astronaut conducts training exercises in the Neutral Buoyancy Simulator – a huge, water-filled tank that simulates weightlessness.



Gallery 5.5 Hubble's First Repair Mission (STS-61)

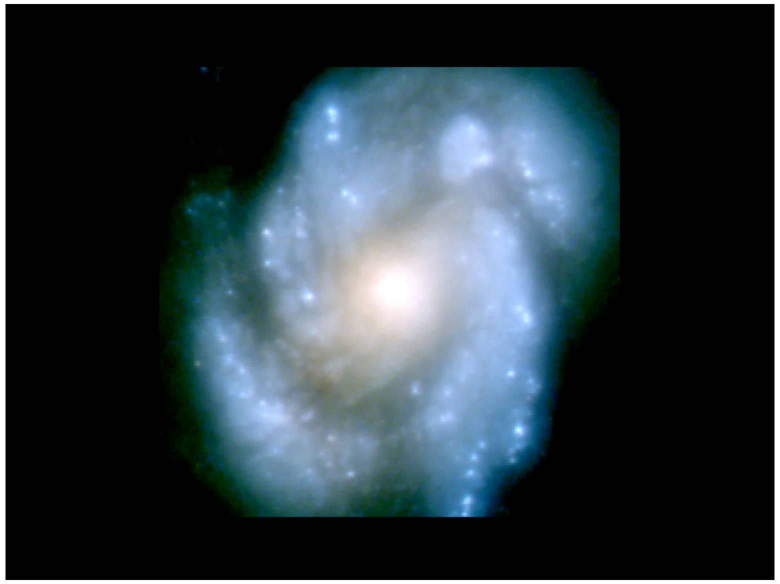


The Space Shuttle Endeavour approaches the Hubble Space Telescope on a backdrop of the Indian Ocean.



NASA released the first new images from Hubble's fixed optics on January 13, 1994. The pictures were beautiful; their resolution, excellent. Hubble was transformed into the telescope that had been originally promised.

Interactive 5.4 Compare Hubble's Old and New Optics with M100 Galaxy Core

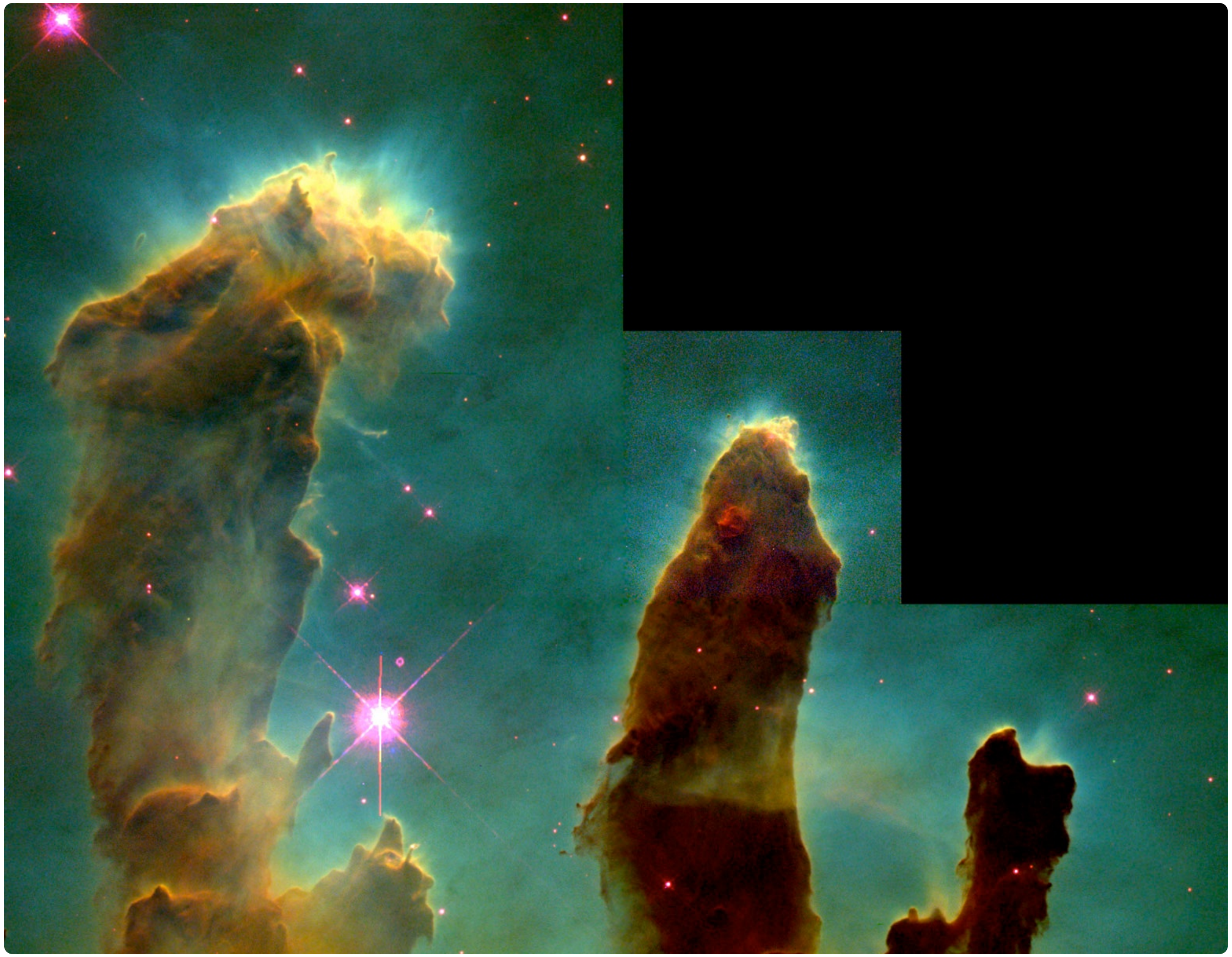


1993 Mission Patches

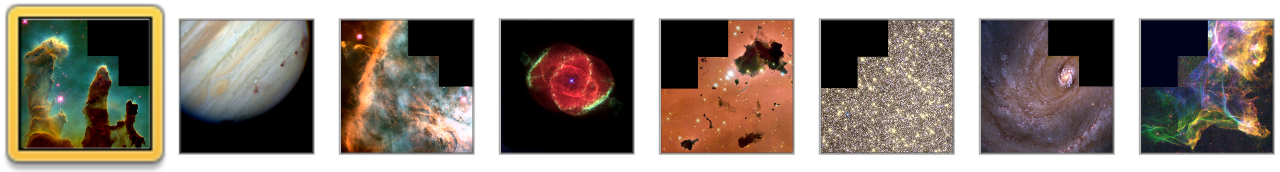
Hubble Servicing Mission 1 (SM1)

Shuttle Mission STS-61

Gallery 5.6 Images from Wide Field Planetary Camera 2



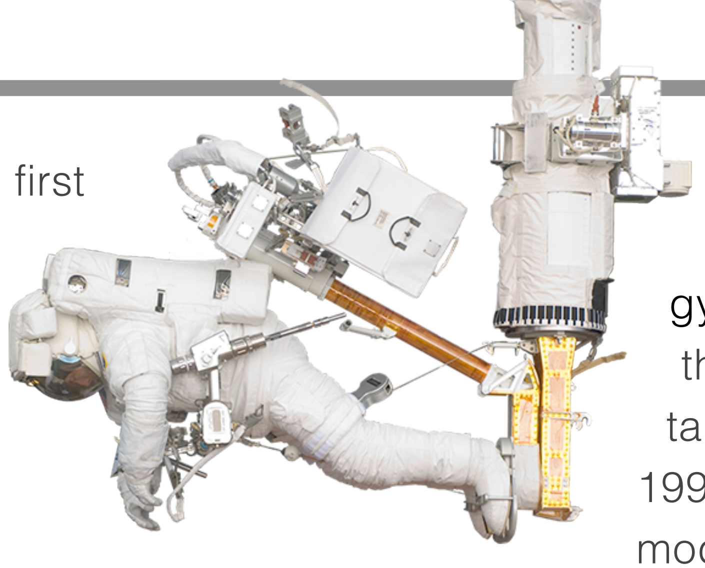
One of Hubble's most famous images, Pillars in the Eagle Nebula (M16)



SECTION 4

Servicing Missions

Hubble overshadows Astronauts Smith and Grunsfeld during the telescope's third repair mission in December 1999.



Hubble's servicing mission in 1993 was the first of many successful attempts to both upgrade the telescope and keep it running smoothly. Hubble would be visited by astronauts in 1997, 1999, 2002 and 2009.

In 1997, the space shuttle brought Hubble a pair of gifts, two instruments featuring technology that wasn't available when scientists designed and built the original equipment. The new instruments gave Hubble a keener gaze on the cosmos, a pattern that would be repeated in following years as astronauts brought Hubble improved technology with each visit.

The third servicing mission ended up being split into two parts, Servicing Mission 3A in December 1999, and Servicing Mission 3B three years later. The voyage had become critical – three of Hubble's six gyroscopes had failed, and Hubble was thought to need at least three to observe a target. A fourth gyroscope failed in November 1999, requiring Hubble to be put into "safe mode," in which it was protected but could not observe targets.

An urgent "call-up" mission was quickly approved, developed and executed in a record seven months. During Servicing Mission 3A, astronauts replaced all six gyroscopes and installed more powerful electronics and batteries, and new insulation.

Servicing Mission 3B, saw the installation of both Hubble's powerful Advanced Camera for Surveys (ACS) and a new

Hubble Mission Patches

Servicing Mission 2 (SM2), 1997

Servicing Mission 3A (SM3A), 1999

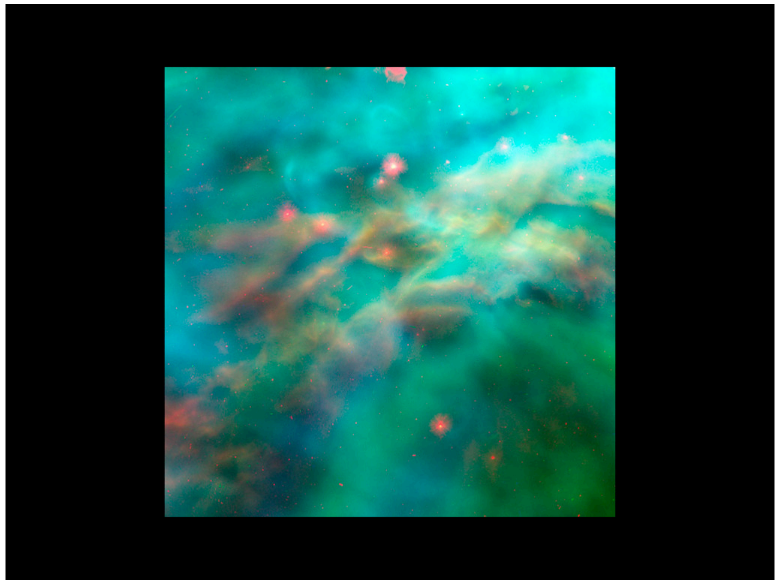
Servicing Mission 3B (SM3B), 2002

Servicing Mission 4 (SM4), 2009

Power Control Unit. The mission was a delicate one – to replace the power unit, Hubble had to be turned off for the first time since its launch. But the mission went as planned and ACS, with its wide field of view, superb image quality, and exquisite sensitivity, brought 10 times more discovery power than the camera it replaced.

The last servicing mission to Hubble in May 2009 was the culmination of a long effort to provide the telescope with one more astronaut visit. Originally scheduled for 2004, Servicing Mission 4 was postponed and then cancelled after the loss of the Space Shuttle Columbia.

Interactive 5.5 Hubble's View Improves Over Time



Hubble images of a small region of the Orion Nebula show how the telescope's vision has improved over time.

Following the restart of the shuttle program and a re-examination of risks, NASA approved another mission. Servicing Mission 4 was perhaps Hubble's most challenging and intense servicing mission.

In late September 2008, only two weeks before the mission was to launch, a malfunction occurred in one of the systems that commands the science instruments and directs the flow of data within the telescope. The problem was fixed by switching to a backup system, but NASA was unwilling to leave the telescope without a spare. The mission was delayed until May while engineers and scientists tested and prepared an existing and nearly identical system.

Shuttle Mission Patches

Shuttle Mission STS-82 (SM2), 1997

Shuttle Mission STS-103 (SM3A), 1999

Shuttle Mission STS-109 (SM3B), 2002

Shuttle Mission STS-125 (SM4), 2009

At the time, two of Hubble’s primary instruments had already stopped working; ACS after an electrical short in 2007, and the Space Telescope Imaging Spectrograph (STIS) after a power failure in 2004.

During Servicing Mission 4, astronauts were able to install a replacement data unit, but also accomplished a feat never envisioned by the telescope creators – on-site repairs for the two failed instruments. To perform the repairs, astronauts had to crack into the interior of the instruments, switch out components, and reroute power – all during spacewalks.

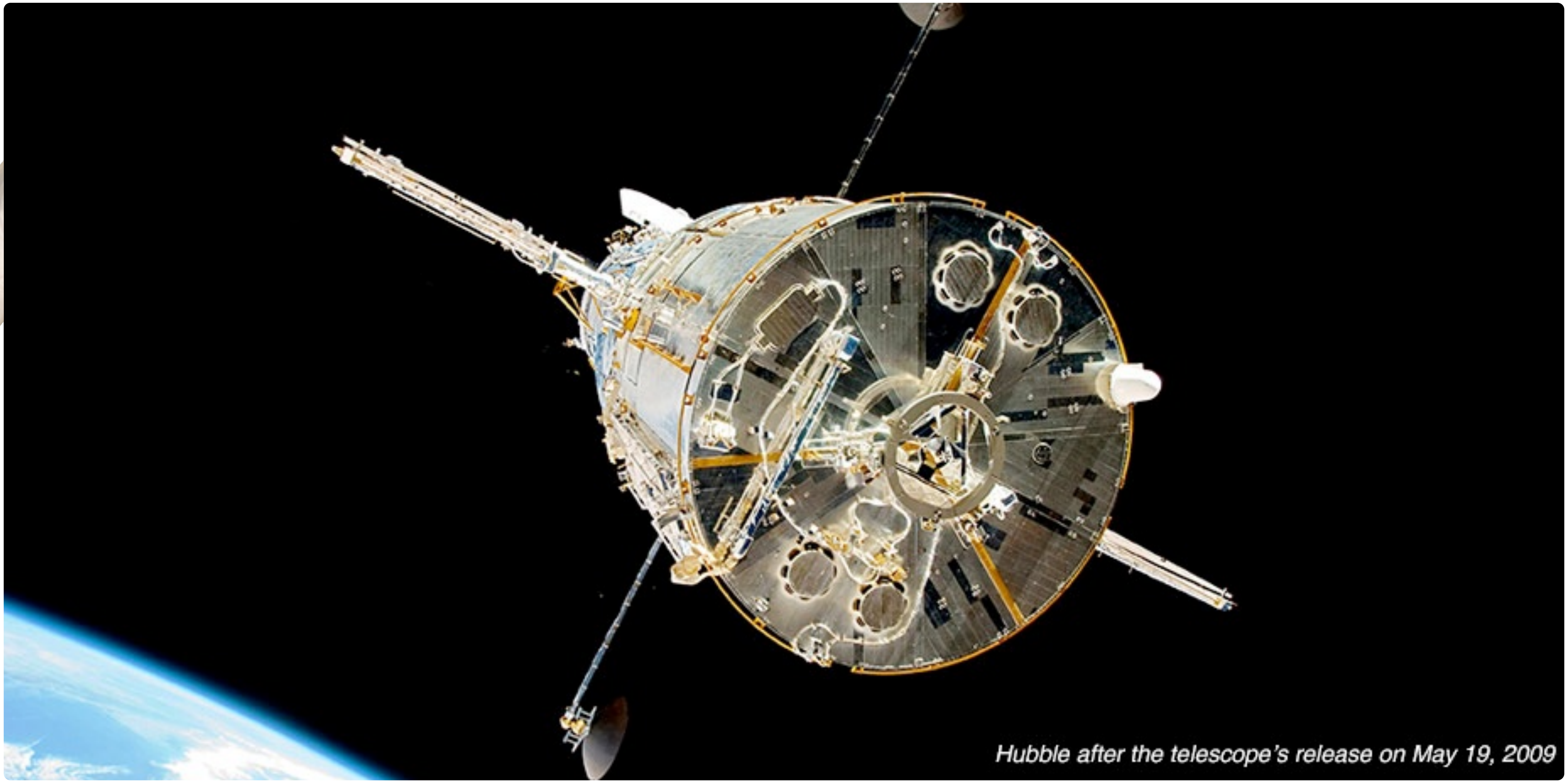
The successful completion of Hubble’s nail-biting repairs, along with the addition of two new advanced instruments – Wide Field Camera 3 (WFC3) and the Cosmic Origins Spectrograph (COS) – gave Hubble a full house of five functioning instruments for its future observations. WFC3, Hubble’s latest workhorse instrument, is highly sensitive and efficient, and can take pictures in ultraviolet, optical and infrared light. COS is a spectrograph that examines both nearby stars and distant galaxies, as well as the gas and dust in between.

Since SM4 is expected to be the last astronaut mission to Hubble, astronauts also installed a new device, the Soft Capture Mechanism. This simple device will allow a robotic spacecraft to attach itself to Hubble someday, once the telescope is at the end of its life, and guide it through its descent into Earth’s atmosphere.

Movie 5.2 STS-125 Launch for Hubble Servicing Mission 4

On May 11, 2009, Space Shuttle Atlantis and the STS-125 crew lift off on the final mission to upgrade Hubble.

All Good Things ...

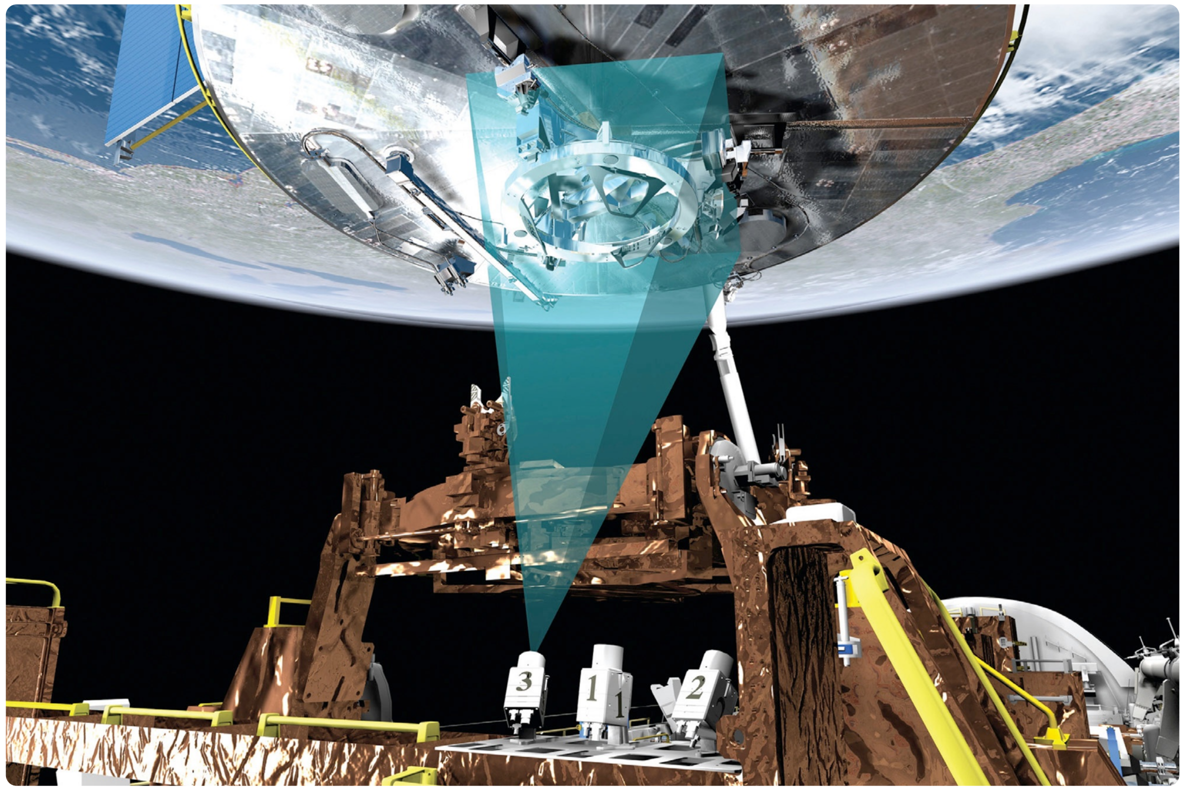


Hubble after the telescope's release on May 19, 2009

Eventually, Hubble's time will end. As the years progress, Hubble's components will slowly degrade to the point at which the telescope stops working.

When that happens, Hubble will continue to orbit Earth until its orbit decays, allowing it to spiral toward Earth. Though NASA originally hoped to bring Hubble back to Earth for

Figure 5.6 Preparing for the Future

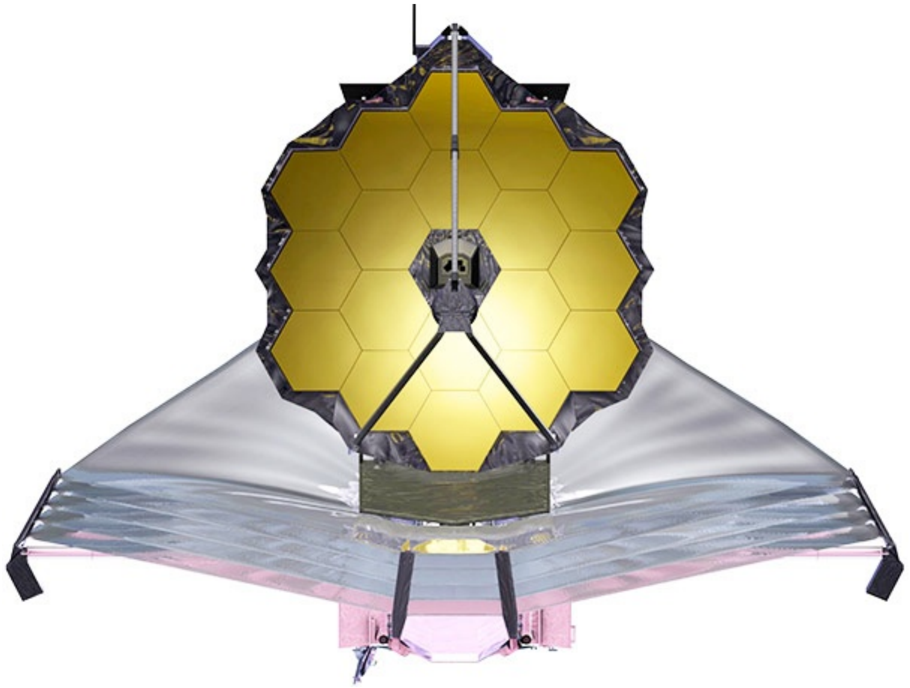


During the 2009 servicing mission to Hubble, an imaging system called the Relative Navigation System (RNS) acquired images and video of the telescope's aft bulkhead as the shuttle released it back into space. This information will enable NASA to pursue numerous options for the safe de-orbit of Hubble. This artist's depiction shows one of the RNS cameras collecting data.

museum display, the telescope's prolonged lifespan has placed it beyond the date for the retirement of the space shuttle program. Hubble was designed specifically to function with the space shuttle, so the replacement vehicle will likely not be able to return it to the ground. A robotic mission is expected to help de-orbit Hubble, guiding its remains through a plunge through the atmosphere and into the ocean.

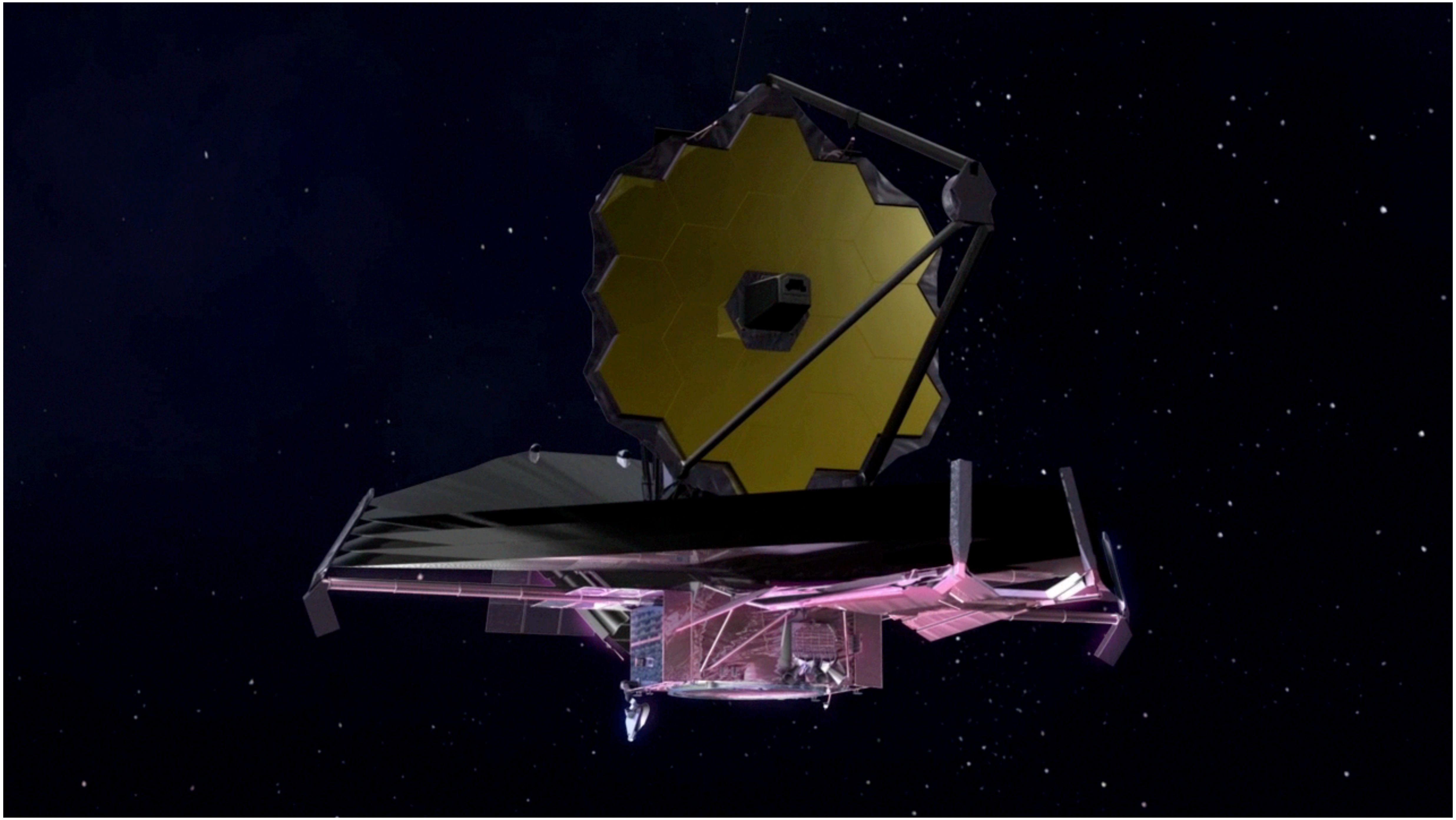
But Hubble's legacy – its discoveries, its trailblazing design, its success in showing us the universe in unparalleled detail – will live on. Scientists will rely on Hubble's revelations for years as they continue in their quest to understand the cosmos – a quest that has attained clarity, focus, and triumph through Hubble's rich existence.

Hubble's eventual death will not be the final chapter in space telescope exploration of the universe. Hubble's successor, the James Webb Space Telescope, will be the next giant observatory in space. Webb, which will see infrared light as well as Hubble sees in visible light, will be a tennis court-sized telescope orbiting far beyond Earth's moon.



SECTION 6

Beyond Hubble



Movie 5.3 **Introducing the James Webb Space Telescope**

The James Webb Space Telescope is NASA's next orbiting observatory and the successor to the Hubble Space Telescope. Webb will soar through a frigid void nearly a million miles from Earth, peering back to the time when new stars and developing galaxies first began to illuminate the universe.

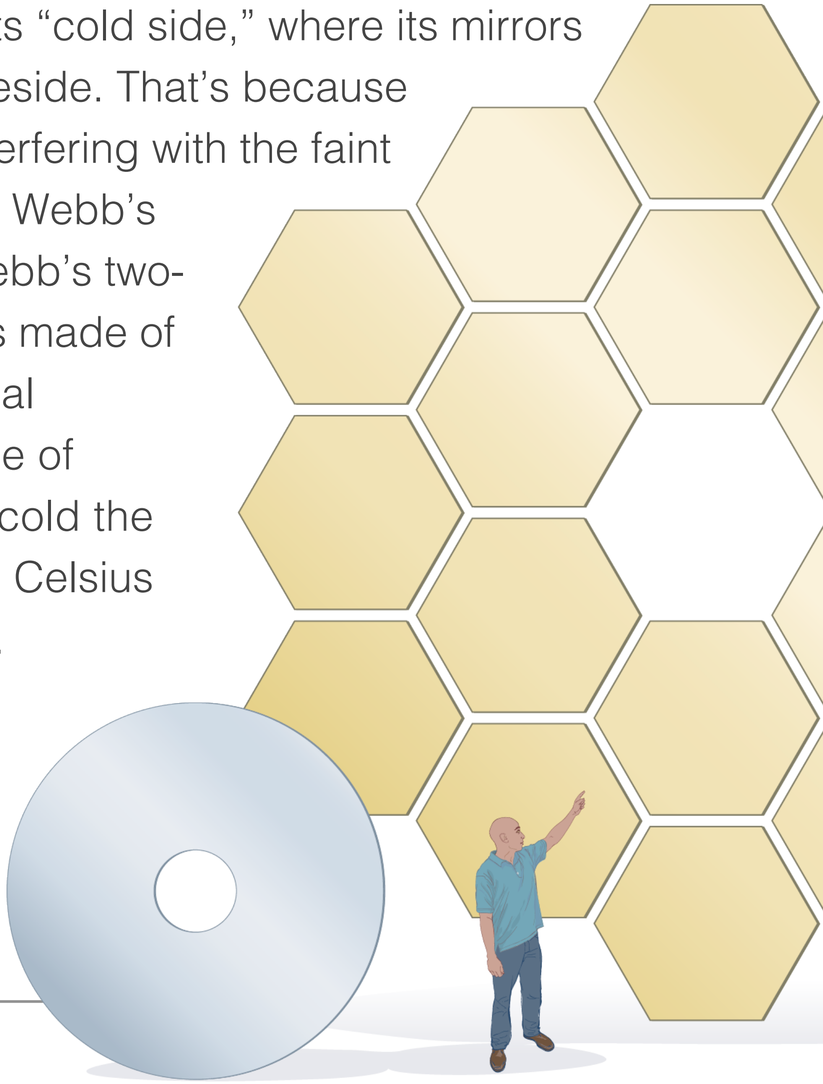
Interactive 5.6 Visible vs. Infrared: A Stellar Jet in Carina

Hubble images demonstrate how observations taken in visible and in infrared light reveal dramatically different and complementary views of an object.

Webb will scan the cosmos for the invisible radiation called infrared. Infrared vision is vital to our understanding of the universe: The furthest objects we can detect are seen in infrared light, cooler objects that would otherwise be invisible to us emit infrared, and infrared light pierces clouds of dust, allowing us to see into their depths.

Webb will see infrared as clearly and precisely as Hubble sees visible light.

Webb doesn't look much like our idea of a telescope. For one thing, it has no tube, just a tennis court-sized sunshield that stops light from reaching its "cold side," where its mirrors and science instruments reside. That's because a tube would trap heat, interfering with the faint infrared radiation reaching Webb's mirror and instruments. Webb's two-story-high primary mirror is made of 18 segments of the material beryllium, which is capable of withstanding the extreme cold the telescope will face: -233.3 Celsius (-388 degrees Fahrenheit).



The Webb Telescope's primary mirror, at 255.6 inches (6.5 meters), is too large to be monolithic like Hubble's 94.5-inch (2.4-meter) mirror. Therefore, it's mirror is divided into 18 precisely ground and polished hexagonal segments.

Webb will be the largest telescope ever placed in orbit. To get this huge telescope into space, it will have to be folded up inside the rocket that carries it from Earth. It will unfurl as it nears its destination, the mirror unfolding and the sunshield spreading like wings.

With its infrared vision, Webb will be able to see light from vast distances that has been stretched as it travels across the expanding fabric of space – a process known as “redshifting.” This will enable scientists to see the light from the first galaxies to form in the early universe – the first flicker of stars that formed after the Big Bang.

Hubble has seen the adult, teenage and child galaxies of the universe, but Webb will see the cosmos’ toddlers and infants.

Webb’s infrared view will allow us to see through opaque clouds of gas and dust in our own galaxy to objects within, like newborn stars and dusty disks forming new solar systems, expanding and deepening our knowledge about how stars and planets develop.

And Webb’s instruments will be able to analyze the light from planets around other stars, allowing us to search for traces of water vapor that could indicate the presence of life-giving oceans. Webb’s vision will be able to detect features in the atmosphere of a planet that could show biological activity.

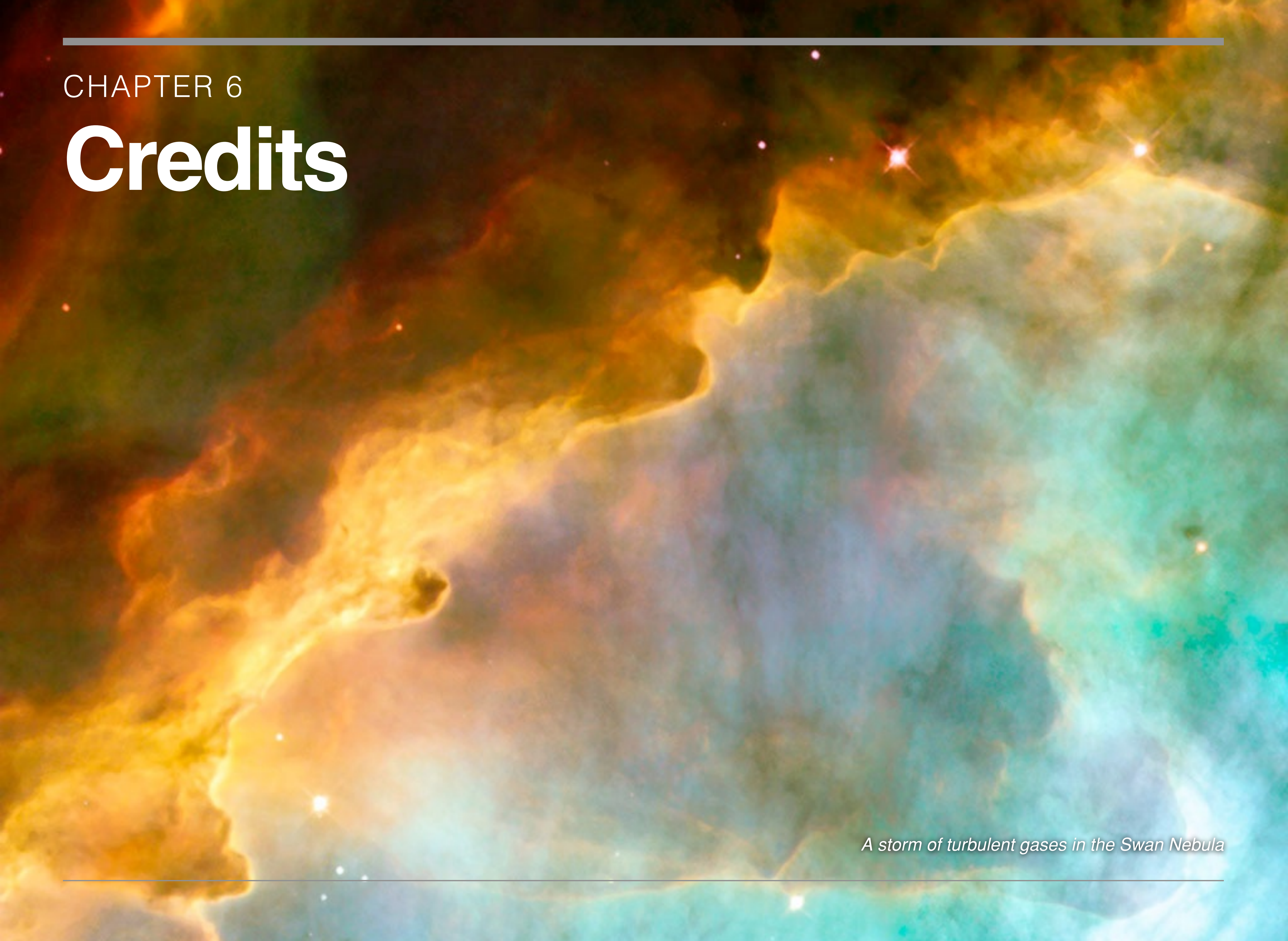
Webb’s launch is scheduled for 2018. And despite the high expectations for the telescope, the true excitement will come from the discoveries Webb makes that no one planned. When Webb takes its place among the stars, it will give astronomers an unprecedented tool to explore the cosmos. The greatest science it reveals may – as with Hubble – open avenues to questions astronomers have not yet thought to ask. The true power of Webb may be its potential for unbounded, unexpected discovery.

Gallery 5.7 Webb Science Targets

A simulated image gives a hint of what deep-field images will look like with Webb. Far-distant galaxies reveal new galactic populations.

CHAPTER 6

Credits



A storm of turbulent gases in the Swan Nebula

Contributors

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Mario Livio, Frank Summers

Many thanks to our colleagues at STScI and NASA's GSFC, including Bonnie Eisenhamer, Stratis Kakadelis, and Pam Jeffries

Credits

Cover

Astronomical image credit: NASA, ESA, and M. Livio and the Hubble 20th Anniversary Team (STScI)
Earth image credit: NASA
Hubble image credit: NASA

Chapter 1: Introduction

PAGE 1

Wide View of Mystic Mountain (HH 901)
Credit: NASA, ESA, and M. Livio and the Hubble 20th Anniversary Team (STScI)

PAGE 3

Hubble Over Earth
Earth image credit: Image Science and Analysis Laboratory, NASA-Johnson Space Center
Hubble image credit: NASA

PAGE 4

Movies 1.1 – 1.6
Hubblecast episode 42: Hubble's Greatest Hits
Credit: ESA/Hubble
Visual design and editing: Martin Kornmesser
Filming: Herbert Zodet
Animations: Martin Kornmesser and Luis Calçada
Web and technical support: Lars Holm Nielsen and Raquel Yumi Shida
Written and directed by: Oli Usher
Interviews by: Oli Usher
Presented by: Dr J (Joe Liske)
Music: movetwo
Executive producer: Lars Lindberg Christensen

Section 1: Gallery

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Mosaic of Hubble images
Credit: NASA, C. Godfrey and J. Bintz (STScI)

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Gallery 1.1

- *Star Cluster NGC 2074 in the Large Magellanic Cloud*
  Credit: NASA, ESA, and M. Livio (STScI)
- *The Retina Nebula: Dying Star IC 4406*
  Credit: NASA and the Hubble Heritage Team (STScI/AURA)
- *Star Cluster NGC 3603*
  Credit: NASA, ESA, and the Hubble Heritage (STScI/AURA)-ESA/Hubble Collaboration
- *Optical and X-ray Composite Image of SNR 0509-67.5*
  Credit: NASA, ESA, CXC, SAO, the Hubble Heritage Team (STScI/AURA), and J. Hughes (Rutgers University)
- *Gas Pillars in the Eagle Nebula (M16)*
  Credit: NASA, ESA, STScI, J. Hester and P. Scowen (Arizona State University)
- *Star-Forming Region S106*
  Credit: NASA, ESA, and the Hubble Heritage Team (STScI/AURA)
- *SN 1006 Supernova Remnant*
  Credit: NASA, ESA, and the Hubble Heritage Team (STScI/AURA)
- *Star-Forming Region 30 Doradus*
  Credit: NASA, ESA, and F. Paresce (INAF-IASF, Bologna, Italy), R. O'Connell (University of Virginia, Charlottesville), and the Wide Field Camera 3 Science Oversight Committee
- *Nearby Galaxy NGC 602*
  Credit: NASA, ESA, and the Hubble Heritage Team (STScI/AURA) - ESA/Hubble Collaboration

- *Pismis 24 and NGC 6357*
  Credit: NASA, ESA, and J. Maíz Apellániz (Instituto de Astrofísica de Andalucía, Spain)
- *The Trifid Nebula*
  Credit: NASA and Jeff Hester (Arizona State University)
- *Infant Stars in the Small Magellanic Cloud*
  Credit: NASA, ESA and A. Nota (STScI/ESA)

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Gallery 1.2

- *Merging Galaxy Cluster Abell 520*
  Credit: NASA, ESA, CFHT, CXO, M.J. Jee (University of California, Davis), and A. Mahdavi (San Francisco State University)
- *Abell 1689 Hubble ACS/WFC*
  Credit: NASA, ESA, E. Jullo (Jet Propulsion Laboratory), P. Natarajan (Yale University), and J.-P. Kneib (Laboratoire d'Astrophysique de Marseille, CNRS, France)
- *NASA's Great Observatories Examine the Galactic Center Region*
  Credit: NASA, ESA, SSC, CXC, and STScI
- *Galaxy Field in Fornax*
  Credit: NASA, ESA, and the Hubble Heritage Team (STScI/AURA)
- *Black Hole in Galaxy M87 Emits Jet of High-Speed Electrons*
  Credit: NASA and John Biretta (STScI/JHU)
- *Lensing Galaxy Cluster Abell 383*
  Credit: NASA, ESA, J. Richard (Center for Astronomical Research/Observatory of Lyon, France), and J.-P. Kneib (Astrophysical Laboratory of Marseille, France)
- *Dark Matter Ring in Galaxy Cluster CL0024+17 (ZwCl0024+1652)*
  Credit: NASA, ESA, M.J. Jee and H. Ford (JHU)
- *GOODS South Deep (GSD)*
  Credit: NASA, ESA, A. van der Wel (Max Planck Institute for Astronomy, Heidelberg, Germany), H. Ferguson and A. Koekemoer (STScI), and the CANDELS team
- *Pandora's Cluster – Abell 2744*
  Credit: NASA, ESA, J. Merten (Institute for Theoretical Astrophysics, Heidelberg/ Astronomical Observatory of Bologna), and D. Coe (STScI)
- *Hubble Ultra Deep Field WFC3/Infrared*
  Credit: NASA, ESA, G. Illingworth and R. Bouwens (University of California, Santa Cruz), and the HUDF09 Team

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Gallery 1.3

- *Saturn and its Moons*
  Credit: NASA, ESA, and E. Karkoschka (University of Arizona)
- *Neptune - Natural Color with Satellites*
  Credit: NASA, ESA, E. Karkoschka (University of Arizona), and H.B. Hammel (Space Science Institute, Boulder, CO)
- *Hubble's Closest View of Mars – 8/27/03*
  Credit: NASA, J. Bell (Cornell University) and M. Wolff (SSI)
- *Pluto and Its Moons*
  Credit: NASA, ESA, H. Weaver (JHU/APL), A. Stern (SwRI), and the HST Pluto Companion Search Team
- *Jupiter and Ganymede (WFPC2 – 4/9/07)*
  Credit: NASA, ESA, and E. Karkoschka (University of Arizona)
- *Rings and Moons Circling Uranus*
  Credit: NASA and Erich Karkoschka, University of Arizona
- *Images of the Asteroid/Dwarf Planet Ceres*
  Credit: NASA, ESA, J. Parker (Southwest Research Institute), P. Thomas (Cornell University), L. McFadden (University of Maryland, College Park), and M. Mutchler and Z. Levay (STScI)
- *Venus Cloud Tops*
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- *Jupiter Map*
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Direction: Frank Summers (STScI)
Narration: Barbara Feldon
Musical score: Jonn Serrie
Production: Greg Bacon, Lynn Barranger, Ann Feild, Leigh Fletcher, Lisa Frattare, John Godfrey, Zoltan Levay, Bryan Preston, John Stoke, Frank Summers, and Ed Weibe (STScI)
Images: NASA's Hubble Space Telescope as part of the Great Observatory Origins Deep Survey (GOODS) project
Support: Lucy Albert, Ian Griffin, and Ray Villard (STScI), and Jim O'Leary (Maryland Science Center)
Digital and 15/70 Post Production: David Keighley Productions 70MM Inc., an IMAX Company

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  Credit: NASA, ESA, R. Windhorst, S. Cohen, M. Mechtley, and M. Rutkowski (Arizona State University, Tempe), R. O'Connell (University of Virginia), P. McCarthy (Carnegie Observatories), N. Hathi (University of California, Riverside), R. Ryan (University of California, Davis), H. Yan (Ohio State University), and A. Koekemoer (STScI)

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Visualization: NASA and F. Summers (STScI)
Simulation: Martin White and Lars Hernquist, Harvard University

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Visual design and editing: Martin Kornmesser
Web and technical support: Raquel Yumi Shida and Mathias André
Written by: Oli Usher
Interviews: Mary Estacion (NASA/STScI)

Animations: Frank Summers and Greg Bacon (NASA/STScI)
Narration: Dr J (Joe Liske)
Images: NASA, ESA
Music: John Stanford from Deep Space
Directed by: Oli Usher
Executive producer: Lars Lindberg Christensen

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Earth image credit: NASA Goddard Space Flight Center. Image by Reto Stöckli (land surface, shallow water, clouds). Enhancements by Robert Simmon (ocean color, compositing, 3D globes, animation). Data and technical support: MODIS Land Group; MODIS Science Data Support Team; MODIS Atmosphere Group; MODIS Ocean Group Additional data: USGS EROS Data Center (topography); USGS Terrestrial Remote Sensing Flagstaff Field Center (Antarctica); Defense Meteorological Satellite Program (city lights)

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Web technical support: Lars Holm Nielsen and Raquel Yumi Shida
Written by: Colleen Sharkey
Narration: Gaitee Hussain
Music: movetwo and John Dyson from the CD Darklight
Select still images: NASA, ESA, NASA/JPL-Caltech and Hermann-Oberth-Raumfahrt-Museum e.V.
Select video footage: NASA
Directed by: Colleen Sharkey
Executive producer: Lars Lindberg Christensen
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Swan Nebula
Credit: NASA, ESA and J. Hester (ASU)

Asteroid

A small solar system object composed mostly of rock. Many of these objects orbit the Sun between Mars and Jupiter. Their sizes range anywhere from 33 feet (10 meters) in diameter to less than 620 miles (1,000 kilometers). The largest known asteroid, Ceres, has a diameter of 579 miles (926 kilometers).

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Chapter 4 - Solar System Comet Crashes

Big Bang

A broadly accepted theory for the origin and evolution of our universe. The theory says that the observable universe started roughly 13.7 billion years ago from an extremely dense and incredibly hot initial state.

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Black hole

A region of space containing a huge amount of mass compacted into an extremely small volume. A black hole's gravitational influence is so strong that nothing, not even light, can escape its grasp. Swirling disks of material – called accretion disks – may surround black holes, and jets of matter may arise from their vicinity.

Related Glossary Terms

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Comet

A ball of rock and ice, often referred to as a “dirty snowball.” Typically a few kilometers in diameter, comets orbit the Sun in paths that either allow them to pass by the Sun only once or that repeatedly bring them through the solar system (as in the 76-year orbit of Halley’s Comet). A comet’s “signature” long, glowing tail is formed when the Sun’s heat warms the coma or nucleus, which releases vapors into space.

Related Glossary Terms

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Chapter 4 - Solar System Comet Crashes

Dark matter

Matter that is too dim to be detected by telescopes. Astronomers infer its existence by measuring its gravitational influence. Dark matter makes up most of the total mass of the universe.

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Density

The ratio of the mass of an object to its volume. For example, water has a density of one gram of mass for every milliliter of volume.

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Elliptical galaxies

Galaxies that appears spherical or football-shaped. Elliptical galaxies are comprised mostly of old stars and contain very little dust and “cool” gas that can form stars.

Related Glossary Terms

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Chapter 2 - Lurking Black Holes

Galactic disk

A flattened disk of gas and young stars in a galaxy. Some galactic disks have material concentrated in spiral arms (as in a spiral galaxy) or bars (as in barred spirals).

Related Glossary Terms

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Chapter 3 - Tracing Galactic Histories

Gamma rays

The part of the electromagnetic spectrum with the highest energy; also called gamma radiation. Gamma rays can cause serious damage when absorbed by living cells.

Related Glossary Terms

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Gravity

(Gravitational force) The attractive force between all masses in the universe. All objects that have mass possess a gravitational force that attracts all other masses. The more massive the object, the stronger the gravitational force. The closer objects are to each other, the stronger the gravitational attraction.

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Chapter 4 - Birth of Stars and Planets

Gyroscopes

A gyroscope is a spinning wheel mounted on a movable frame that assists in stabilizing and pointing a space-based observatory. Gyroscopes are important because they measure the rate of motion as the observatory moves and help ensure the telescope retains correct pointing during observations. The gyroscopes provide the general pointing of the telescope while the fine guidance sensors provide the “fine tuning.” Gyroscopes are used in navigational instruments for aircraft, satellites, and ships. The Hubble Space Telescope has six gyroscopes for navigation and sighting purposes.

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Interstellar dust

Small particles of solid matter, similar to smoke, in the space between stars.

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Chapter 5 - How It Works

Jets

Narrow, high-energy streams of gas and other particles generally ejected in two opposite directions from some central source. Jets appear to originate in the vicinity of an extremely dense object, such as a black hole, pulsar, or protostar, with a surrounding accretion disk. These jets are thought to be perpendicular to the plane of the accretion disk.

Related Glossary Terms

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Chapter 4 - Birth of Stars and Planets

Near-infrared

The region of the infrared spectrum that is closest to visible light. Near-infrared light has slightly longer wavelengths and slightly lower frequencies and energies than visible light.

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Near-ultraviolet

The region of the ultraviolet spectrum that is closest to visible light. Near-ultraviolet light has slightly shorter wavelengths and slightly higher frequencies and energies than visible light.

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Neutron star

An extremely compact ball of neutrons created from the central core of a star that collapsed under gravity during a supernova explosion. Neutron stars are extremely dense: they are only 10 kilometers or so in size, but have the mass of an average star (usually about 1.5 times more massive than our Sun). A neutron star that regularly emits pulses of radiation is known as a pulsar.

Related Glossary Terms

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Observatories

Structures designed and equipped for making astronomical observations. Observatories are located on Earth and in space.

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Organic molecule

Contains carbon atoms. Organic molecules are essential to life. They are normally produced by living organisms and found within them.

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Chapter 4 - Extrasolar Planets

Quasars

The brightest type of active galactic nucleus, believed to be powered by a supermassive black hole. The word “quasar” is derived from quasi-stellar radio source, because this type of object was first identified as a kind of radio source. Quasars also are called quasi-stellar objects (QSOs). Thousands of quasars have been observed, all at extreme distances from our galaxy.

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Radiation

The process by which electromagnetic energy moves through space as vibrations in electric and magnetic fields. This term also refers to radiant energy and other forms of electromagnetic radiation, such as gamma rays and X-rays.

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Chapter 4 - Birth of Stars and Planets

Radio wave

The part of the electromagnetic spectrum with the lowest energy. Radio waves are the easiest way to communicate information through the atmosphere or outer space.

Related Glossary Terms

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Chapter 2 - Lurking Black Holes

Resolution

(Resolving power) A measure of the smallest separation at which a telescope can observe two neighboring objects as two separate objects.

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Satellite galaxies

Galaxies that orbit a larger galaxy which are gravitationally bound

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Chapter 3 - Dying Stars

Satellites

A man-made object that orbits Earth, the Moon, or another celestial object.

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Chapter 3 - Gone in a Flash

Soft Capture Mechanism

When Hubble reaches the end of its mission, NASA must be able to safely return the telescope to Earth. When that time comes, the space shuttle will no longer be operating, so another means of capturing the telescope must be available. The soft capture mechanism is a compact device that, when attached to the Hubble Space Telescope, will assist in its safe de-orbit. This device has structures and targets that will allow a next generation space vehicle to more easily capture and guide the telescope into a safe, controlled re-entry.

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Solar arrays

Two rigid, wing-like arrays of solar panels that convert sunlight directly into electricity to operate the Hubble Space Telescope's scientific instruments, computers, and radio transmitters. Some of the energy generated is stored in onboard batteries so the telescope can operate while in Earth's shadow (which is about 36 minutes out of each 97-minute orbit). The solar arrays are designed for replacement by visiting astronauts during servicing missions.

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Supermassive black hole

A black hole possessing as much mass as a million or a billion stars. Supermassive black holes reside in the centers of galaxies and are the engines that power active galactic nuclei and quasars.

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Chapter 2 - Lurking Black Holes

Supernovae

The explosive death of a massive star whose energy output causes its expanding gases to glow brightly for weeks or months. A supernova remnant is the glowing, expanding gaseous remains of a supernova explosion.

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Chapter 2 - Lurking Black Holes

Visible

(Visible light) The part of the electromagnetic spectrum that human eyes can detect; also known as the visible spectrum. The colors of the rainbow make up visible light. Blue light has more energy than red light.

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Chapter 5 - How It Works

Wavelength

Light is measured by its wavelength (in nanometers) or frequency (in Hertz). One wavelength equals the distance between two successive wave crests or troughs. Radio waves can have lengths of several feet; the wavelengths of X-rays are roughly the size of atoms.

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