A golden era of space exploration and discovery began April 24, 1990, with the launch and deployment of NASA's Hubble Space Telescope (HST). During nearly 10 years of operation, Hubble's rapid-fire rate of unprecedented discoveries has invigorated astronomy. Not since the invention of the telescope nearly 400 years ago has our vision of the universe been so revolutionized over such a short stretch of time.

As the 12.5-ton Earth-orbiting observatory looks into space unburdened by atmospheric distortion, new details about planets, stars, and galaxies come into crystal clear view. The Telescope has produced a vast amount of information and a steady stream of images that have astounded the world's astronomical and scientific communities. It has helped confirm some astronomical theories, challenged others, and often come up with complete surprises for which theories do not yet even exist.

Hubble was designed to provide three basic capabilities:

- High angular resolution – the ability to image fine detail
- Ultraviolet performance – the ability to produce ultraviolet images and spectra
- High sensitivity – the ability to detect very faint objects.

Each year NASA receives over a thousand new observing proposals from astronomers around the world. Observing cycles are routinely oversubscribed by a factor of three or greater.

The Telescope is extremely popular because it allows scientists to get their clearest view ever of the cosmos and to obtain information on the temperature, composition, and motion of celestial objects by analyzing the radiation emitted or absorbed by the objects. Results of HST observations are being presented regularly in scientific papers at meetings of the American Astronomical Society and other major scientific conferences.

Although Hubble's dramatic findings to date are too numerous to be described fully in this Media Reference Guide, the following paragraphs highlight some of the significant astronomical discoveries and observations in three basic categories:

- Planets
- Formation and evolution of stars and planets
- Galaxies and cosmology.

For further detailed information, visit the Space Telescope Science Institute website at: http://oposite.stsci.edu.

3.1 Planets

Since 1990 Hubble has kept an "eye" on our solar system planets: a comet slamming into Jupiter, clouds on Uranus, monster storms on Neptune, auroras on Jupiter and Saturn, and unusual weather on Mars.

Mars. The Telescope captured images of an enormous cyclonic storm system raking the northern polar regions of Mars on April 27, 1999 (see Fig. 3-1). Nearly four times the size of Texas, the storm consists of water ice clouds like those found in storm systems on Earth rather than the dust typically found on Mars. Although similar to so-called "spiral" storms observed more than 20 years ago by NASA's Viking Orbiter spacecraft, this Martian storm is nearly three times the size of the largest previously detected Martian storm system.

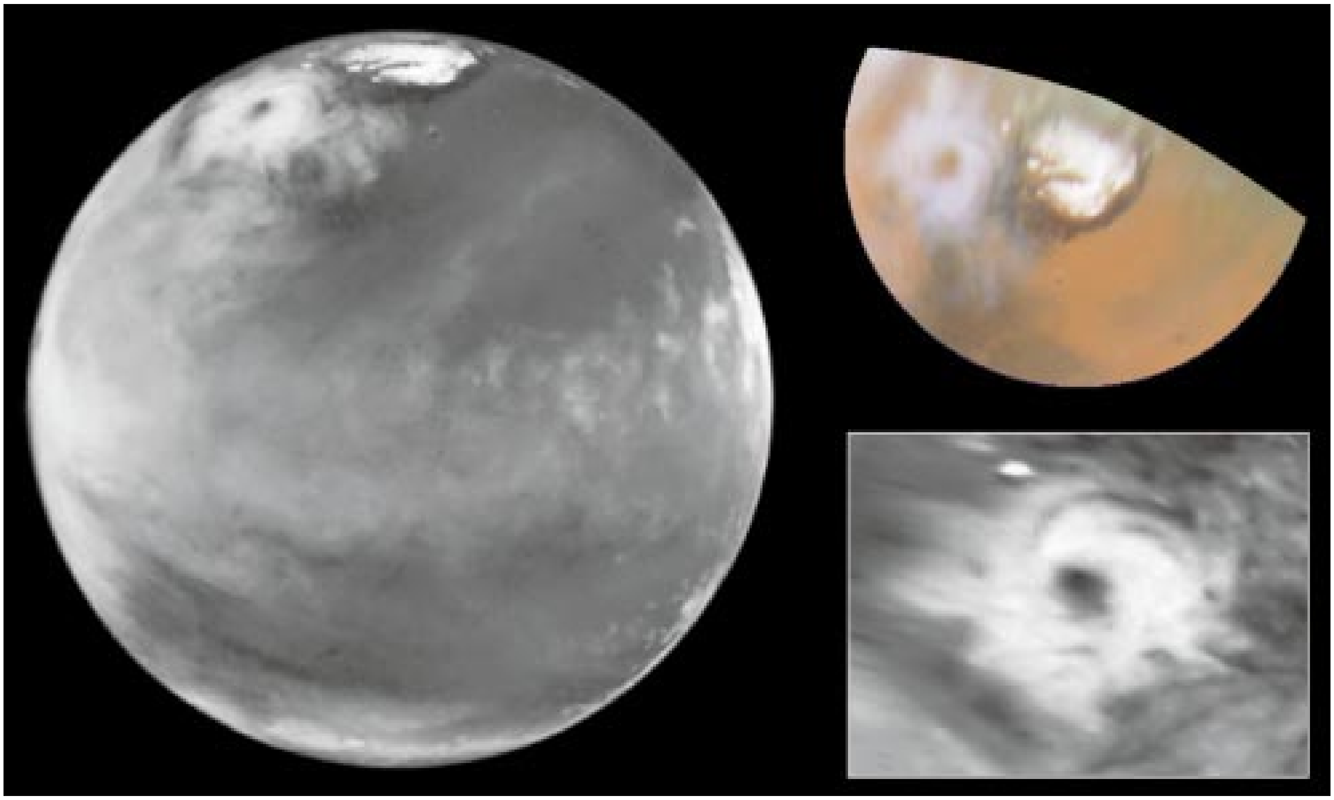

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Fig. 3-1 On April 27, 1999, Hubble took pictures of a Martian storm more than 1000 miles (1600 km) across. Left: an image of the polar storm as seen in blue light (410 nm). Upper right: a polar view of the north polar region, showing the location of the storm relative to the classical bright and dark features in this area. Lower right: an enhanced view of the storm processed to bring out additional detail in its spiral cloud structures.

The Telescope monitored the Red Planet's weather in the spring and summer of 1997, providing detailed reports to help plan the landing of NASA's Mars Pathfinder and the arrival of Mars Global Surveyor. Pictures taken about a week before the landing of the Pathfinder spacecraft show a dust storm churning through the deep canyons of Valles Marineris, just 600 miles (1,000 kilometers) south of the landing site. Remarkable changes in the behavior of dust and water ice clouds on the planet were recorded from July 9 to 11, indicating that weather changes on Mars are very rapid – possibly chaotic.

Hubble took pictures of the entire planet of Mars during its closest approach to Earth in eight years: 54 million miles (87 million kilometers). Using the HST images, astronomers made a full-color global map of Mars (see Fig. 3.2). Latitudes below about 60 degrees south were not viewed because the planet's north pole was tilted towards Earth during that time.

Saturn and Jupiter. Astronomers used Hubble's ultraviolet-light camera, the Space Telescope Imaging Spectrograph (STIS), to probe auroras – curtains of light that seem to dance above the north and south poles of Saturn and Jupiter.

Saturn's auroras rise more than 1,000 miles above the cloud tops (see Fig. 3-3). Like those on Earth, these auroral displays are caused by an energetic wind from the Sun that sweeps over the planet. But unlike Earth, Saturn's auroras have been seen only in ultraviolet light.

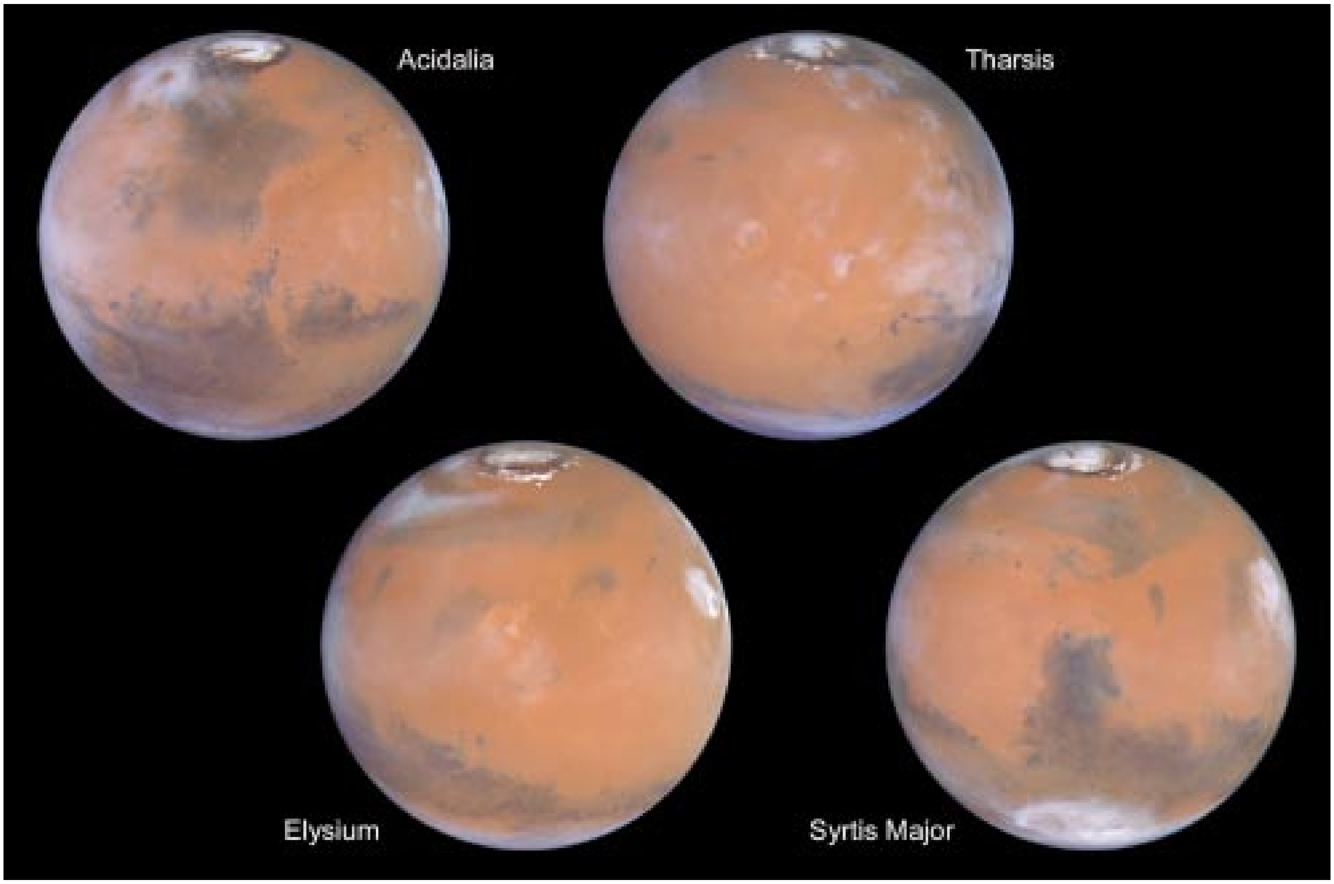

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Fig. 3-2 The HST WFPC2 captured these images between April 27 and May 6, 1999, when Mars was 54 million miles (87 million kilometers) from Earth. From this distance the telescope could see Martian features as small as 12 miles (19 kilometers) wide.

The auroras are primarily shaped and powered by a continual tug-of-war between Saturn's magnetic field and the flow of charged particles from the Sun.

The Telescope has also taken many images of Jupiter's aurora in ultraviolet light. Jovian auroral storms develop when electrically charged particles trapped in the magnetic field surrounding the planet spiral inward at high energies toward the north and south magnetic poles. As these particles strike the upper atmosphere, they excite atoms and molecules there, causing them to glow.

Hubble's Near Infrared Camera and Multi-Object Spectrometer (NICMOS) has provided a multicolor view of Saturn, giving detailed information on the clouds and hazes in the planet's atmosphere (see Fig. 3-4).

The blue colors in the NICMOS image of Saturn indicate a clear atmosphere down to a main cloud layer. Most of the northern hemisphere visible above the rings is relatively clear. The dark region around the south pole corresponds to the region of auroral activity and displays different reflective properties. The green and yellow colors define a haze above the main cloud layer; the haze is thin where the colors are green and thick where they are yellow. Due to Saturn's east-west winds, these layers are aligned along latitude lines. The red and orange colors indicate clouds reaching high into the atmosphere. Red clouds are higher than orange clouds. The densest regions of two storms near Saturn's equator appear white.

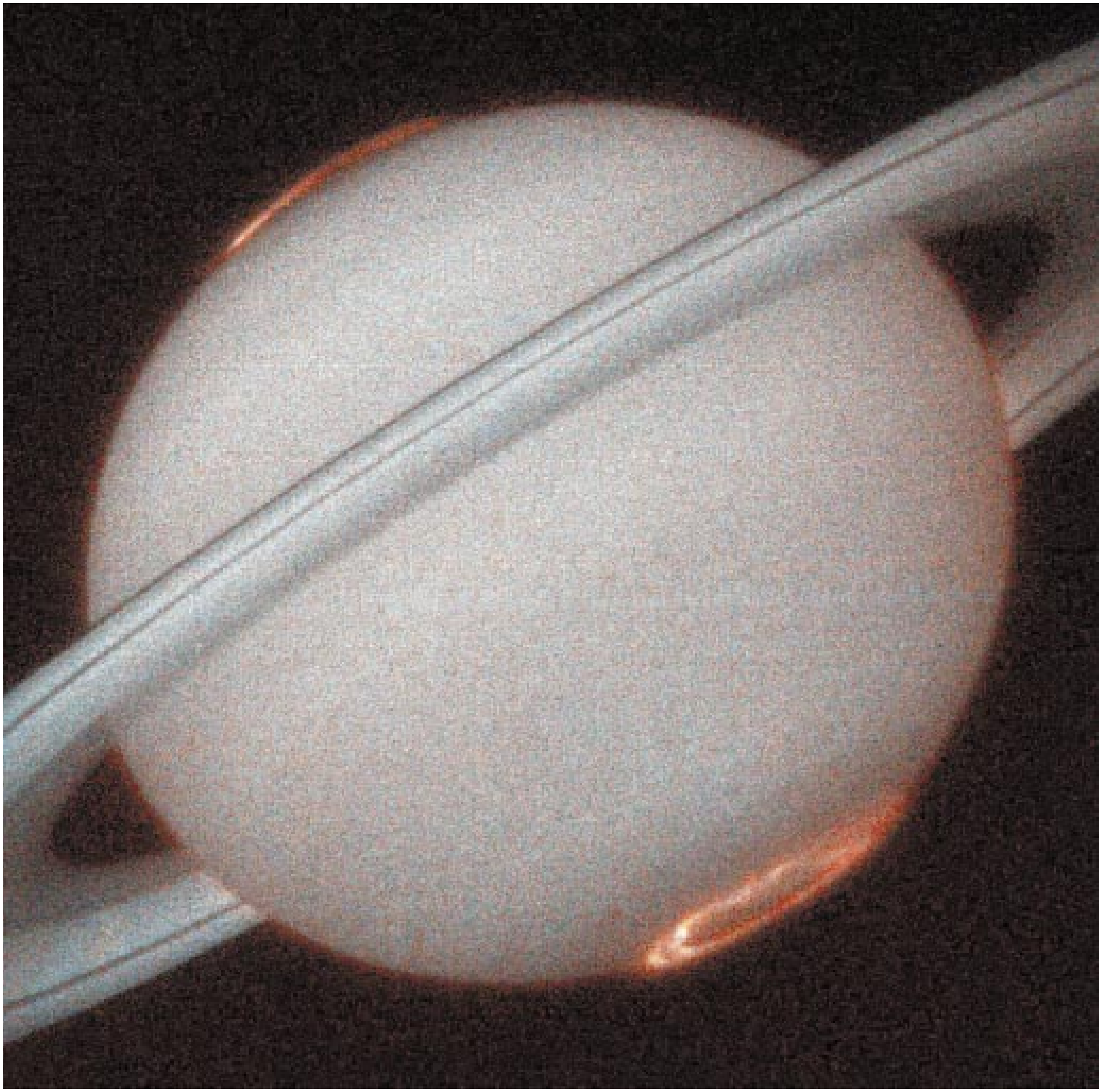

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Fig. 3-3 This is the first image of Saturn's ultraviolet aurora taken by the STIS in October 1997, when Saturn was 810 million miles (1.3 billion kilometers) from Earth.

The Telescope captured an invasion of Jupiter in 1994 when 21 fragments of the comet Shoemaker-Levy 9 slammed into the giant planet. As each comet fragment crashed into Jupiter, mushroom-shaped plumes were expelled from the planet. The largest fragment impacts created Earth-sized "bull's-eye" patterns on Jupiter. Hubble's record of the comet's bombardment, combined with results from other space-borne and Earth-based telescopes, sheds new light on Jupiter's atmospheric winds and its immense magnetic field.

Uranus. Astronomers used Hubble images, taken from 1994 to 1998, to create a time-

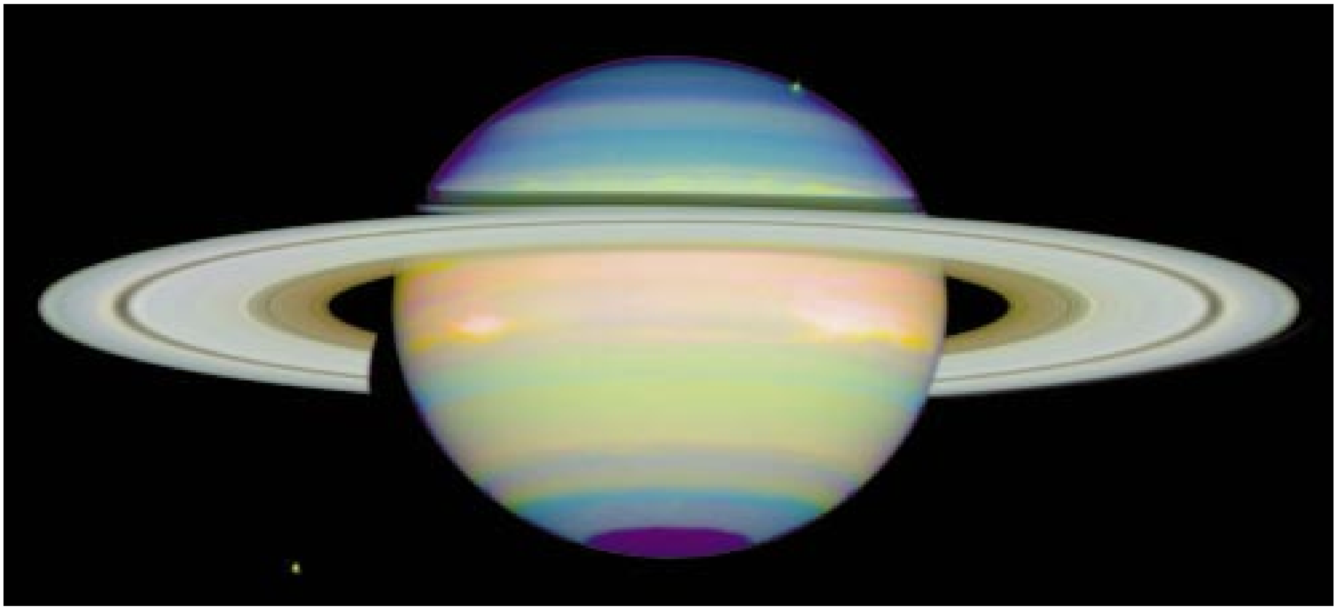

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Fig. 3-4 Saturn viewed in the infrared shows atmospheric clouds and hazes.

lapse movie that shows, for the first time, seasonal changes on Uranus. Once considered a bland-looking planet, Uranus is now revealed as a dynamic world with rapidly changing bright clouds – some circling the planet at more than 300 miles per hour – and a fragile ring system that wobbles like an unbalanced wagon wheel. The clouds probably are made of crystals of methane, which condense as warmer bubbles of gas well up from deep in the planet's atmosphere. The movie clearly shows for the first time the wobble in the ring system, comprising billions of tiny pebbles. The wobble may be caused by Uranus's shape, which is like a slightly flattened globe, and the gravitational tug from its many moons.

Uranus is tilted completely over on its side, giving rise to 20-year-long seasons and unusual weather. For nearly a quarter of the Uranian year, the Sun shines directly over each pole, leaving the other half of the planet in a long, dark, frigid winter. Now the northern hemisphere of Uranus is coming out of the grip of its two-decade winter.

Neptune. The unusual weather patterns of Neptune also are the subject of a time-lapse rotation movie using HST images. The movie shows that the planet has some of the wildest, weirdest weather in the solar system. The Telescope captured the most insightful images to date of a planet whose blustery weather – monster storms and equatorial winds of 900 miles per hour – is still a mystery to scientists.

Pluto. Even the outermost planet in our solar system hasn't escaped Hubble's scrutiny. The Telescope unveiled the never-before-seen surface of Pluto, orbiting at the dim outer reaches of the solar system nearly three billion miles (five billion kilometers) from the Sun. Pluto is only two-thirds the size of the Earth's moon but is 12,000 times farther away.

The Faint Object Camera (FOC) imaged nearly the entire surface of Pluto as it rotated through its 6.4-day period in late June and early July 1994. The images, made in blue light, show that Pluto is an unusually complex object, with large-scale contrast.

3.2 Formation and Evolution of Stars and Planets

Planets form from leftover star-making material, the pancake-shaped disks of dust and gas swirling around nascent stars. Hubble has provided evidence that these disks are common around developing stars. The Telescope also has expanded astronomers' knowledge about the life cycle of stars. It has peeked behind the dusty veil of star birth regions to chronicle the genesis of stars and captured the colorful shrouds around dying stars.

The giant galactic nebula NGC 3603 (see Fig. 3-5) contains a community of stars in various stages

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Fig. 3-5 The crisp resolution of the Telescope reveals various stages of the life cycle of stars in this single view of the giant galactic nebula NGC 3603.

of life. Dark clouds in the upper right are so-called Bok globules, dense clouds of dust and gas that harbor embryonic stars. Giant pillars of gas (below and right of the blue cluster of stars), composed of cold molecular hydrogen, serve as an incubator for new stars. Ultraviolet light from the nearby star cluster is sculpting the pillars, which are reminiscent of the famous pillars the Hubble photographed in the M16 Eagle Nebula.

Below the cluster are two compact, tadpole-shaped protoplanetary disks. Near the center of the image is a starburst cluster dominated by young, hot Wolf-Rayet stars and early O-type stars. A torrent of ionizing radiation and fast stellar winds from these massive stars has blown a large cavity around the cluster. To the upper left of center is the aging blue supergiant Sher 25. The star has a unique ring of glowing gas that is a galactic twin to the famous ring around the exploding star, supernova 1987A.

Are there other planetary systems like our own? If so, how are they created? Astronomers are on the hunt to find out. They are studying debris disks, composed of dust and gas, whirling around developing stars. This dust and gas could eventually clump together to form planets. Hubble has imaged such disks around several stars ranging in age from 1 million to 10 million years. The Telescope's arsenal of cameras has recorded the disks in light from ultraviolet to near infrared. By chronicling the disks at different stages of a star's early life, astronomers are adding information to the planet-making recipe.

Hubble's sharp vision has analyzed disks around a group of nearby young stars in the constellation Taurus. Images taken in the near-infrared as well as visible light reveal how infalling material forms first into a thin disk around the young stars. Then a portion of the disk material is shot back into the interstellar medium in the form of opposing jets that emerge perpendicularly from the center of the disk. The accretion disks are huge, averaging more than ten times the diameter of our solar system.

The Wide Field and Planetary Camera 2 (WFPC2) spotted the first example of an edge-on disk in a young double-star system. The images offer further evidence that planet formation should be possible in binary star systems. Theory holds that gravitational forces between two stars in a binary system tend to tear apart fragile planet-forming disks, but the Hubble images reveal evidence of dust clumping together in the disks – a first step on the long road to planet formation.

Looking at a disk around a slightly older star, astronomers using STIS found evidence of more clumping of material. This two- to four-million-year-old star, called AB Aurigae, is in the constellation Auriga. The clumps are much farther away from the star than is Pluto, the outermost solar system planet, from our Sun.

Turning its gaze to a fully developed star, HR 4796A, about 10 million years old, NICMOS captured images of a wide dust ring (6.5 billion miles). The rings around the star resemble those of Saturn, but on a grander scale. Gaps between the rings could be the result of unseen bodies sweeping out lanes. The star is 220 light-years away in the constellation Centaurus.

Hubble also has provided images of what may be the most luminous known star, called the Pistol Star, which is big enough to fill the diameter of Earth's orbit. This celestial mammoth releases up to 10 million times the power of the Sun, unleashing as much energy in three seconds as our Sun does in one year. The NICMOS image also reveals a bright nebula created by massive stellar eruptions. The nebula is so big (four light-years across) that it would span nearly the distance from the Sun to Alpha Centauri, the nearest star to Earth's solar system.

Astronomers estimate that when the Pistol Star was formed one to three million years ago, it may have weighed up to 200 times the mass of the Sun before shedding much of its bulk in violent eruptions. The star is approximately 25,000 light-years from Earth near the center of the Milky Way.

A star like our Sun spends its embryonic years accumulating mass until it reaches maturity. When it nears the end of its life, it sheds some of its mass as it contracts to a white dwarf. As material ejected from the star is driven outward into space, radiation from the star causes it to glow. The illuminated stellar remains surrounding a dying star are called a planetary nebula. A nebula will shine for about 10,000 years.

Hubble has provided a gallery of these nebulae, which come in many shapes and glow in a kaleidoscope of colors. The Ring Nebula (M57) is a stunning example of a dying central star floating in a blue haze of hot gas (see Fig. 3-6). The colorful nebula surrounding the star

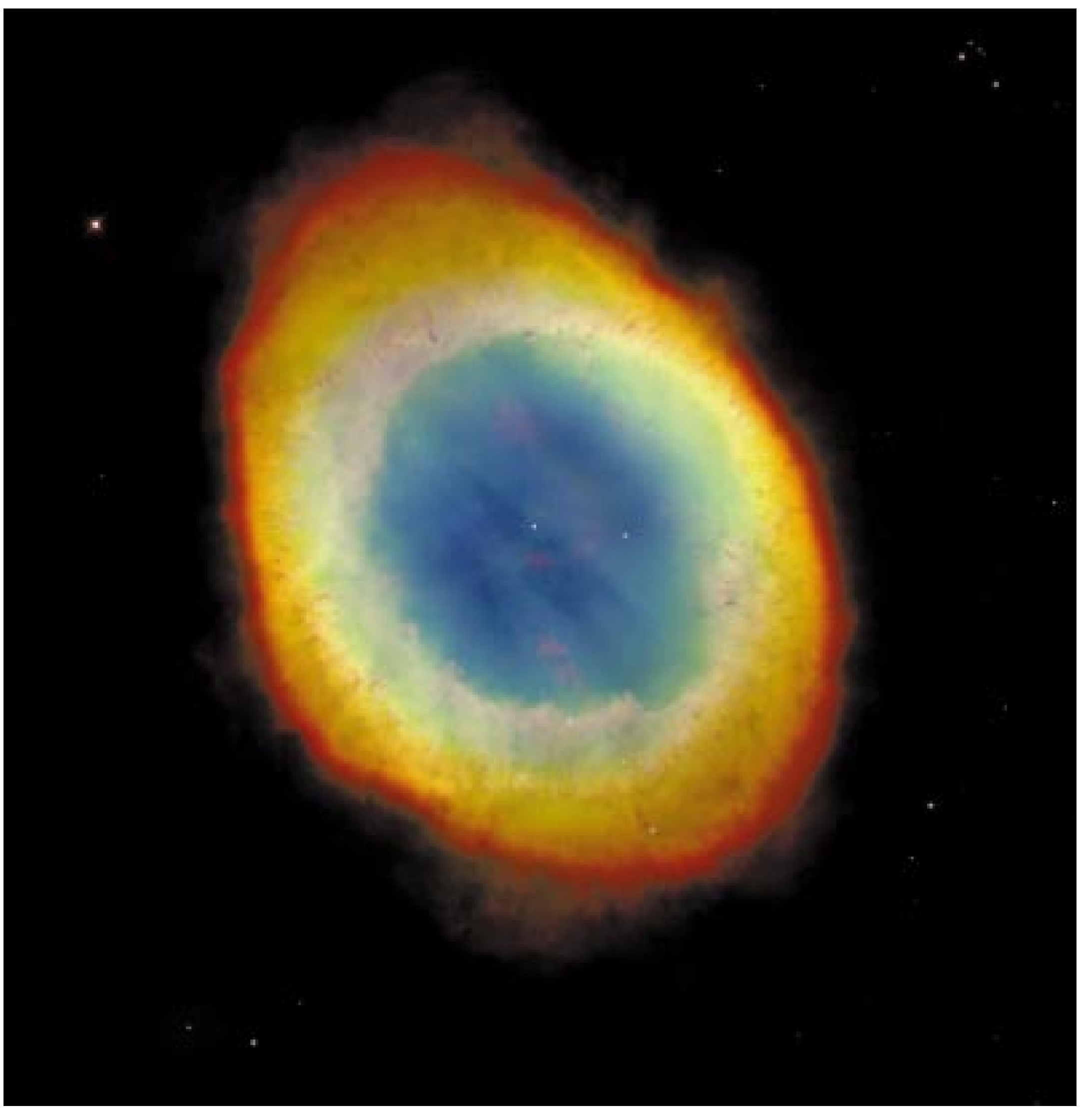

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Fig. 3-6 In this October 1998 image of the Ring Nebula (M57), Hubble looks down a barrel of gas cast off by a dying star thousands of years ago.

appears ring-shaped, but only because of the viewing angle. Many astronomers believe that the nebula is actually a cylinder and the Hubble picture supports this view.

The Telescope's image of the Ring Nebula shows numerous small, dark clouds of dust that have formed in the gas flowing out from the star. They are silhouetted against more distant, bright gas. These finger-like clouds appear only in the outer portions of the Ring Nebula; none are seen in the central region. This suggests that they are not distributed in a uniform sphere but are instead located only on the walls of the barrel, which is a light-year in diameter. The nebula is 2,000 light-years from Earth in the constellation Lyra.

Another striking planetary nebula is M2-9, called a "butterfly" or bipolar planetary nebula because of its shape (see Fig. 3-7). Another more revealing name might be the "Twin Jet Nebula." A companion star orbiting perilously close to its dying mate may have caused the unusual shape. Astronomers suspect the gravity of one star pulls weakly bound gas from the surface of the other and flings it into a thin, dense disk surrounding both stars. The high-speed wind of gas from one of the stars slams into the disk, which serves as a nozzle. Deflected in a perpendicular direction, the wind forms a pair of jets speeding at 200 miles per second. The nebula is 2,100 light-years away in the constellation Ophiuchus.

Unlike lighter-weight stars that quietly end their lives by forming planetary nebulae, massive stars die in mammoth explosions. HST has been monitoring one such explosion, supernova 1987A – 167,000 light-years away in the Large Magellanic Cloud. Scientists first viewed the star's self-destruction on February 23, 1987,

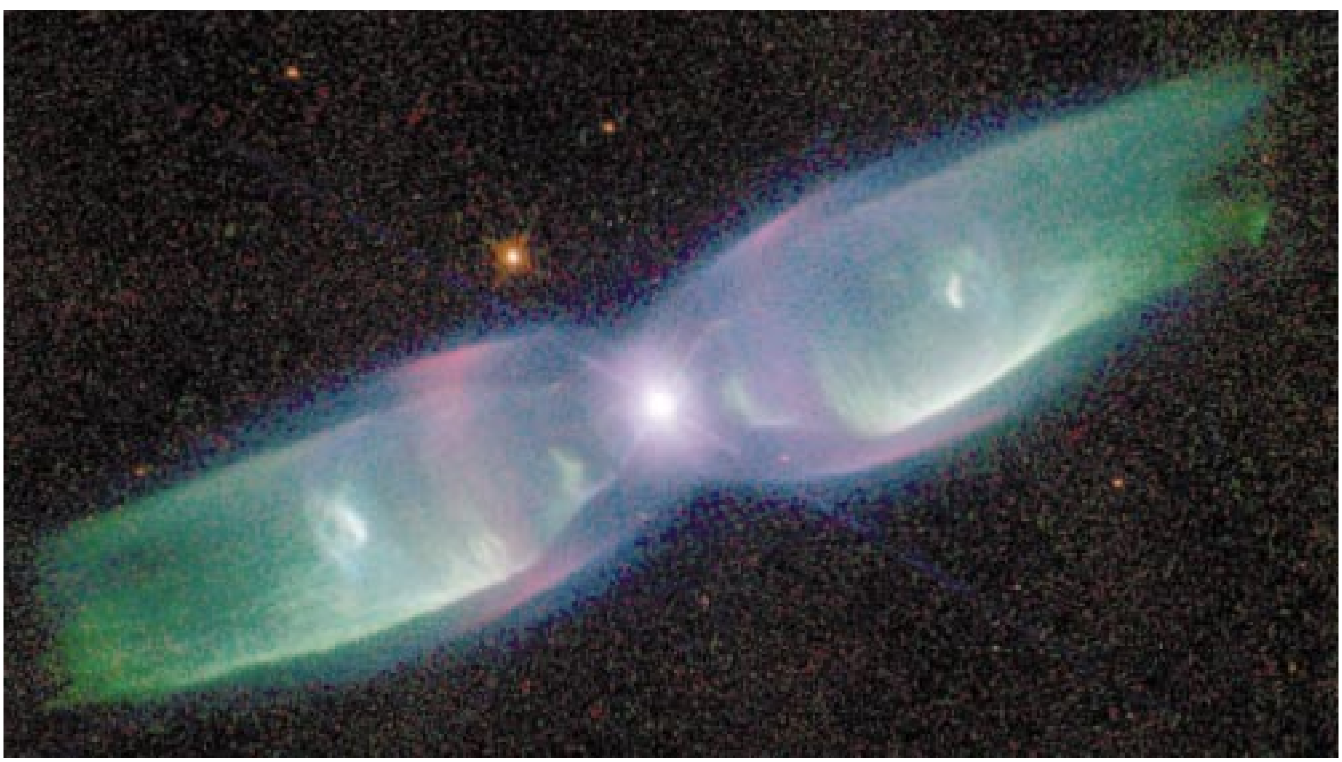

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Fig. 3-7 Hubble sees supersonic exhaust from nebula M2-9, a striking example of a "butterfly" or bipolar planetary nebula.

in a naked-eye observation. In July 1997, STIS captured the first images of material ejected by the exploding star ramming into an inner ring around the dying object (see Fig. 3-8).

Shocked by the 40-million-miles-per-hour sledgehammer blow, a 100-billion-mile-wide knot of gas in a piece of the ring has already begun to “light up” as its temperature surges from a few thousand to a million degrees Fahrenheit. By analyzing the glowing ring, astronomers may find clues to many of the supernova’s unanswered mysteries: What was the progenitor star? Was it a single star or a binary system? What was the process that created a ring that formed 20,000 years before the star exploded?

3.3 Galaxies and Cosmology

Galaxies are the largest assemblages of stars in the universe. In a galaxy, billions of stars are bound together by the mutual pull of gravity. The Sun resides in the Milky Way Galaxy.

The study of galaxies falls into the realm of cosmology, the science of the evolution of the universe on the largest scale. Edwin P. Hubble discovered the expansion of the universe by measuring the redshifts of distant galaxies. He demonstrated that the galaxies are rushing away from us, with their velocities increasing proportionally to their distances. The constant of proportionality is known as the Hubble constant. The reciprocal of the Hubble constant is an index to the age of the universe, or the time since the Big Bang.

Measuring the Hubble constant was a major goal for the Hubble Space Telescope before it was launched in 1990. In May 1999, the Telescope key project team announced that it had completed its efforts to measure precise distances to far-flung galaxies, an ingredient needed to determine the age, size, and fate of the universe. The team measured the Hubble constant at 70 km/sec/Mpc, with an uncertainty of 10 percent. This means that a galaxy

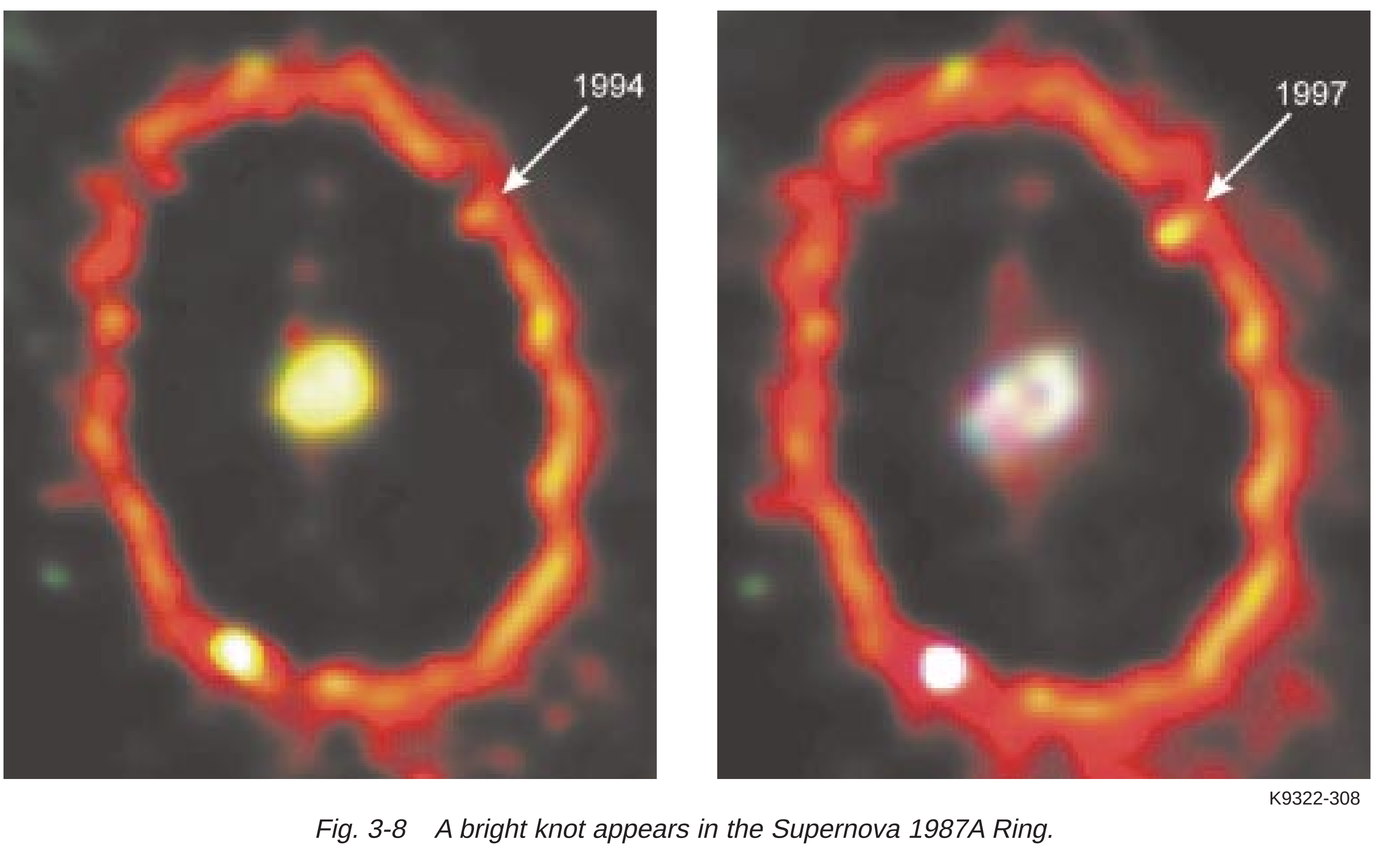

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Fig. 3-8 A bright knot appears in the Supernova 1987A Ring.

appears to be moving 160,000 miles per hour faster for every 3.3 million light-years away from Earth.

Using the Telescope, the team observed 18 galaxies, some as far away as 65 million light-years. The team was looking for Cepheid variable stars, a special class of pulsating star used for accurate distance measurements. Almost 800 Cepheids were discovered. But the team could utilize only Cepheids in nearby and intermediate-distance galaxies. To calculate distances to galaxies farther away, the team used so-called "secondary" distance measurements, such as a special class of exploding star called a Type Ia supernova. Combining the Hubble constant measurement with estimates for the density of the cosmos, the team has determined that the universe is approximately 12 billion years old and that it contains insufficient mass to halt the expansion of space. This was, perhaps, the most important astronomical discovery of the decade.

In December 1995 the Telescope provided humankind's deepest, most detailed visible-light view of the heavens called the Hubble Deep Field. In 1998 Hubble's penetrating vision was turned toward the southern skies. The Telescope peered down a narrow, 11-billion-light-year-long corridor loaded with thousands of never-before-seen galaxies. The observation, called the Hubble Deep Field South (HDF-S), doubles the number of far-flung galaxies available for deciphering the history of the universe. In each "deep field" view, astronomers counted about 3,000 galaxies. Both views also show that galaxies were smaller in the past and have evolved to the giant spirals and ellipticals of today.

The southern "far-look" complements the original Hubble Deep Field, for which Hubble was aimed at a small patch of sky near the Big Dipper. The southern region is in the constellation Tucana, near the south celestial pole. The 10-day HDF-S observation took place in October 1998. At first glance HDF-S appears to validate the common assumption that the universe should look largely the same in any direction (see Fig. 3-9).

The two deep fields give astronomers two "core samples" of the universe to use for better understanding the history of the cosmos. All of Hubble's cameras and other instruments were trained on the sky at the same time for the observations. STIS dissected light from a quasar (the bright, active core of a distant galaxy). This light, which had traveled nearly three-quarters of the way across the heavens, provides a powerful three-dimensional probe of the universe's hidden structure. Invisible clouds of primeval hydrogen gas strung along billions of light-years between HST and the quasar are detectable in the signature of the light. The quasar is so brilliant it is like a searchlight shining through haze.

The Hubble Deep Field uncovered a plethora of odd-shaped, disrupted-looking galaxies. They offer direct evidence that galaxy collisions were more the rule than the exception in the early universe. Because collisions of distant galaxies are too faint and too small to study in much detail, the Telescope turned its gaze to a galactic wreck closer to home – the Antennae galaxies. A pair of long tails of luminous matter formed by a collision resembles an insect's antennae (see Fig. 3-10). The galaxies are 63 million light-years from Earth in the southern constellation Corvus.

At the heart of these colliding galaxies, the Telescope uncovered more than 1,000 bright, young star clusters bursting to life in a brief, intense, brilliant "fireworks show." By probing the

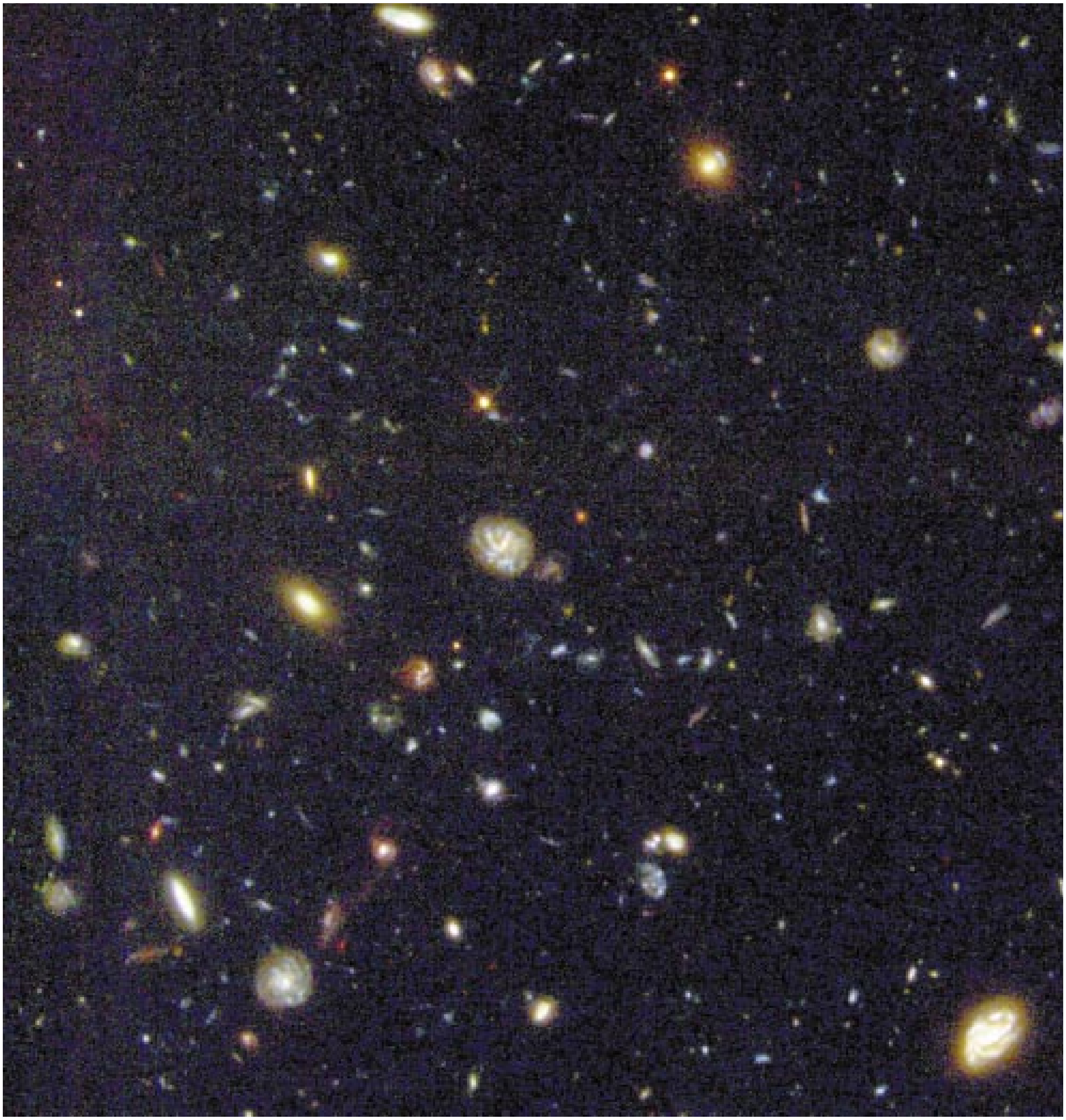

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Fig. 3-9 In an observation called the Hubble Deep Field South (HDF-S), the Telescope peered down an 11-billion-light-year-long corridor loaded with thousands of never-before seen galaxies.

Antennae and other colliding galaxies, Hubble has given astronomers a variety of surprises:

- Globular star clusters are not necessarily relics of the earliest generations of star formation in a galaxy. They may provide fossil records of more recent encounters.
- The "seeds" for star clusters appear to be giant molecular clouds of cold hydrogen gas, tens to hundreds of light-years across. The clouds are squeezed by surrounding hot gas heated during the galaxy collisions, then collapse under their own gravity. Like a string of firecrackers ignited by the collision,

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Fig. 3-10 This HST image provides a detailed look at a "fireworks show" in the center of a collision between two galaxies.

the reservoirs of gas light up in a great burst of star formation.

- The ages of the resulting clusters provide a clock for estimating the age of a collision. This offers an unprecedented opportunity for understanding, step by step, the complex sequence of events that occurs during an encounter and possibly even the evolution of spiral galaxies into elliptical galaxies.

Sometimes the debris from galaxy collisions is fodder for supermassive black holes. HST has given astronomers a peek at a feeding frenzy as a supermassive black hole in a nearby galaxy devours a smaller galaxy after the two collide. Such fireworks were common in the early universe, as galaxies formed and evolved, but are rare today.

The WFPC2 image of Centaurus A, also called NGC 5128, shows in sharp clarity a dramatic dark lane of dust girdling the colliding galaxy (see Fig. 3-11). Blue clusters of newborn stars are clearly resolved, and silhouettes of dust filaments are interspersed with blazing orange-glowing gas. Located 10 million light-years away, this peculiar-looking galaxy contains the closest active galactic nucleus to Earth and has long been considered an example of an elliptical galaxy disrupted by a recent collision with a smaller companion spiral galaxy.

Using NICMOS, astronomers have penetrated this wall of dust for the first time to see a twisted disk of hot gas swept up in the black hole's gravitational whirlpool. The suspected black hole is so dense it contains the mass of perhaps a billion stars,

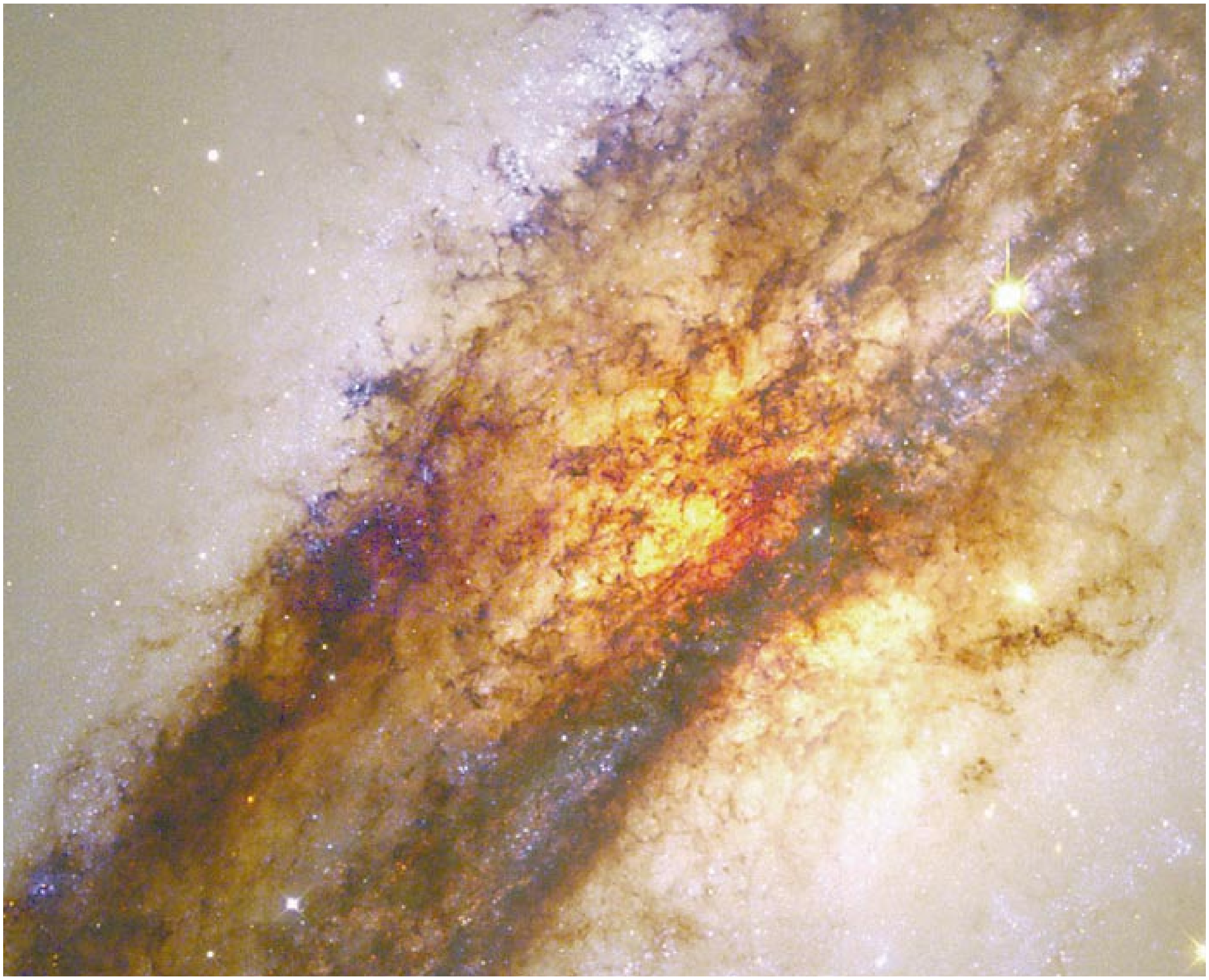

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Fig. 3-11 Hubble offers an unprecedented close-up view of a turbulent firestorm of starbirth along a nearly edge-on dust disk girdling Centaurus A.

compacted into a small region of space not much larger than our solar system.

Resolving features as small as seven light-years across, the Hubble has shown that the hot gas is tilted in a direction different from the axis of the black hole – like a wobbly wheel around an axle. This gas disk presumably fueling the black hole may have formed so recently that it has not yet become aligned with the black hole's spin axis, or it may simply be influenced more by the gravitational tug of the galaxy than by that of the black hole.

Still, scientists do not know if the black hole was always present in the host galaxy, if it belonged to the spiral galaxy that fell into the core, or if it is the product of the merger of a pair of smaller black holes that lived in the two once-separate galaxies.

From invisible black holes to the mysterious flashes of high-energy radiation called gamma ray bursts, Hubble is on the trail. These bright bursts of energy appear from random regions in space and typically last just a few seconds. U.S. Air Force Vela satellites first discovered gamma ray bursts in the 1960s. Since then, numerous theories of their origins have been proposed, but their causes remain unknown. The Telescope has helped astronomers trace them back to distant galaxies. The principal limitation in understanding the bursts was the difficulty in pinpointing their direction in the sky. Unlike visible light, gamma rays are exceedingly difficult to observe with a telescope, and their short duration exacerbates the problem.

Hubble has teamed up with several observatories, including X-ray satellites, to collect information on gamma ray bursts. The most energetic burst, GRB 971214, was detected December 14, 1997. Astronomers measured the distance to a faint galaxy from which the burst originated. Using the Italian / Dutch satellite BeppoSAX, they pinpointed the direction of the burst, which permitted follow-up observations with the world's most powerful telescopes.

The follow-up observations tracked GRB 971214's "afterglow" in radio waves, X-ray, visible, and infrared light. While gamma ray bursts last only a few seconds, their afterglows can be studied for several months. By analyzing afterglows, astronomers have discovered that the bursts do not originate within our own galaxy, the Milky Way, but are associated with extremely distant galaxies. The Hubble images of GRB 971214 confirmed the association of the burst's afterglow with a faint galaxy.

Astronomers still don't understand the origins of gamma ray bursts. Theories suggest they happen where vigorous star formation takes place. Whatever are the origins of gamma ray bursts, the Telescope has observed many of them, and in nearly every case they have been found to be associated with faint host galaxies.

3.4 Summary

The Hubble Space Telescope has established itself as a premier astronomical observatory that continues to make dramatic observations and discoveries at the forefront of astronomy. Following the successful First and Second Servicing Missions, the Telescope has achieved all of its original objectives. Among a long list of achievements, Hubble has:

- Improved our knowledge of the size and age of the universe
- Provided decisive evidence of the existence of supermassive black holes at the centers of galaxies
- Clearly revealed the galactic environments in which quasars reside
- Detected objects with coherent structure (protogalaxies) close to the time of the origin of the universe
- Provided unprecedentedly clear images and spectra of the collision of Comet Shoemaker-Levy 9 with Jupiter
- Detected a large number of protoplanetary disks around stars
- Elucidated the various processes by which stars form
- Provided the first map of the surface of Pluto
- Routinely monitored the meteorology of planets beyond the orbit of Earth
- Made the first detection of an ultraviolet high-energy laser in Eta Carinae.

After the Servicing Missions 3A and 3B, the Hubble Space Telescope will view the universe anew with significantly expanded scientific and technological capabilities.