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ENCYCLOPEDIA ARTICLE

Hubble Space Telescope

The *Hubble Space Telescope* is the largest visible-light observatory ever placed into space. *Hubble*'s orbit, some 612 km (380 mi) above Earth's surface (**Fig. 1**), keeps it above almost all of Earth's atmosphere, at a location where its view of the heavens is much clearer than that of ground-based telescopes. The superior view afforded by *Hubble*'s orbit has made the telescope a unique resource for astronomers worldwide and has led to fundamental discoveries about the size and age of the universe, the birth and death of stars, and the development of galaxies.

Fig. 1 *Hubble Space Telescope* in orbit around Earth.

The spacecraft

The *Hubble Space Telescope* is 13.2 m (43.5 ft) long, is 4.2 m (14 ft) in diameter at its widest, weighs 11,110 kg (24,500 lb), and orbits Earth once every 96 minutes. At its core is a reflecting telescope with a primary mirror 2.4 m (94.5 in.) in diameter (**Fig. 2**). The primary mirror directs light from astronomical objects to a 30-cm (12-in.) secondary mirror, which then bounces it back through a hole at the center of the primary mirror to the scientific instruments. The optical design is a Ritchey-Chrétien variant of a Cassegrain telescope.

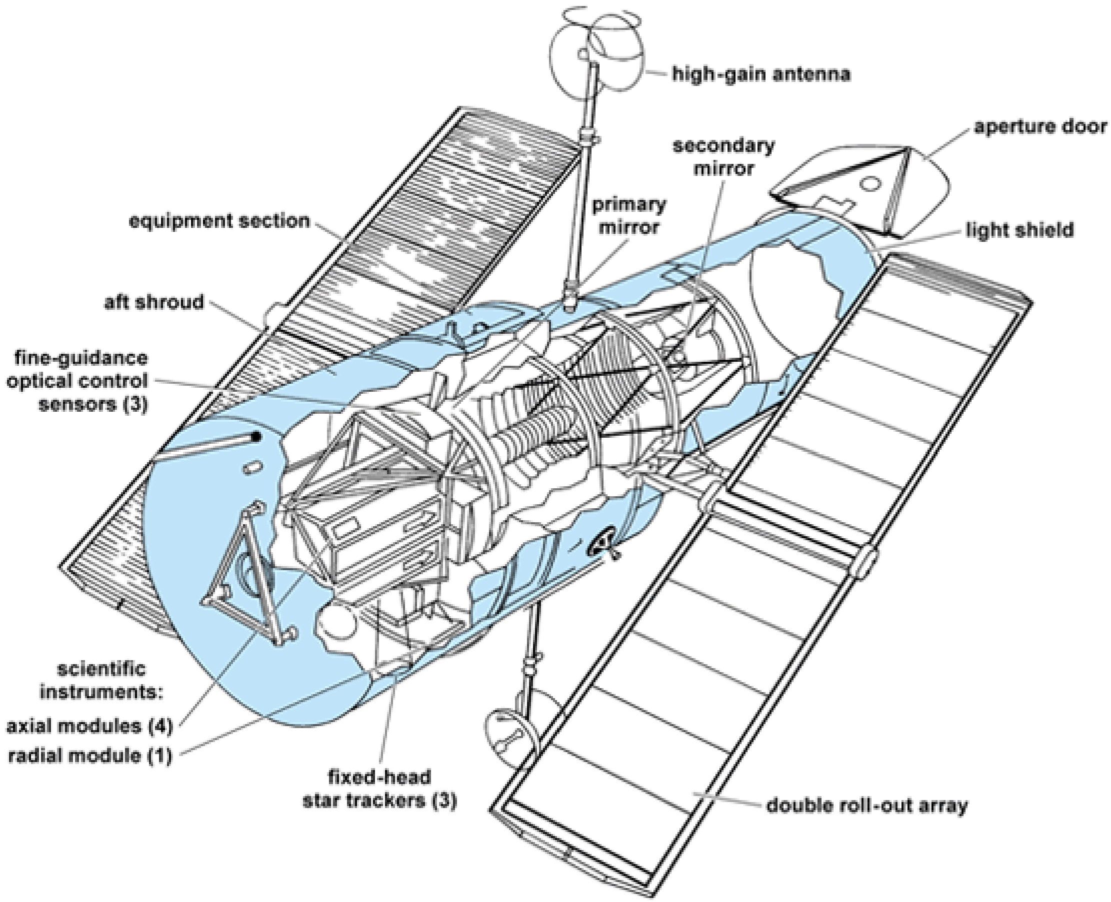

Fig. 2 Diagram of the *Hubble Space Telescope*.

Hubble's optical system enables the telescope to record astronomical images with unprecedented precision in the optical, ultraviolet, and infrared spectral bands. In order to take full advantage of the clearer view above Earth's atmosphere, *Hubble*'s mirrors had to be polished until they were extremely smooth: The largest bumps on *Hubble*'s primary mirror are analogous to the height of a baseball on a surface as wide as the continental United States. A flaw in the overall shape of the primary mirror hampered observations for several years after launch. However, because the primary mirror was so smooth, corrective optics installed in 1993 were able to realize *Hubble*'s expected performance (**Fig. 3**). Its angular resolution of 0.05 arcsecond at optical wavelengths is equivalent to being able to distinguish two fireflies 1 m (3 ft) apart at a distance of 5000 km (3000 mi). See also: Infrared astronomy; Telescope; Ultraviolet astronomy

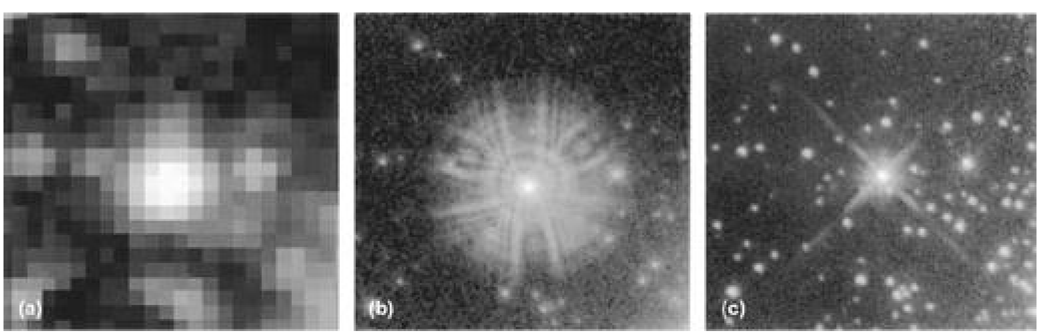

Fig. 3 Comparison of images of a field of stars in the 30 Doradus Nebula. (*a*) Ground-based image obtained under conditions of good seeing. (*b*) Same star field at the same scale taken with the *Hubble Space Telescope* before the first servicing mission. (*c*) *Hubble* image after the first servicing mission when the spherical aberration was corrected.

(*NASA*)

Recording sharp images during exposure times that can approach 1 hour requires very precise and stable pointing of the telescope. Guide stars are used to keep *Hubble* locked on target. Each observation typically relies on two guide stars that *Hubble*'s guiding system keeps fixed at preselected locations in two of its three Fine Guidance Sensors. Whenever *Hubble* drifts slightly off target, the guiding system returns these stars to their preselected locations in the telescope's field of view, placing the telescope back on target. This system keeps *Hubble* pointed to within 0.007 arcsecond, equivalent to keeping a laser in New York locked on a small coin in Washington, DC.

Hubble's complement of scientific instruments handles a wide range of observational tasks. Its cameras have recorded images of astronomical objects at wavelengths ranging from 115 to 2500 nanometers. *Hubble*'s spectrographs have analyzed the spectra of these objects between wavelengths of 115 and 1030 nm. Because these instruments can be removed and replaced, they have been upgraded several times during *Hubble*'s stay in orbit (see **table**). A diverse assortment of support equipment surrounds the telescope and its scientific instruments. To supply power, the spacecraft has two solar arrays and a set of storage batteries that keep the spacecraft operating when it passes through Earth's shadow. To rotate the telescope toward different spots on the sky, *Hubble* has four reaction wheels; increasing their spin rate in one direction causes the spacecraft to rotate in the opposite direction. To store and communicate the data gathered, *Hubble* has a set of solid-state data recorders and communications antennas that link to NASA's Tracking and Data Relay Satellite System (TDRSS). Governing the whole spacecraft is an onboard computer that interprets and executes the instructions relayed from the ground.

History of *Hubble*'s instruments*

	Instruments	Dates
Original instruments	Wide Field/Planetary Camera (WF/PC), *Hubble*'s original visible/ultraviolet light camera	1990–1993
	Faint Object Camera (FOC), *Hubble*'s highest-resolution camera	1990–2002
	Faint Object Spectrograph (FOS), for analyzing light from faint objects	1990–1997
	Goddard High Resolution Spectrograph (GHRS), designed to perform detailed analyses of spectra	1990–1997
	High Speed Photometer (HSP), for measuring rapid variations in the brightness of astronomical objects	1990–1993
Instruments from first servicing mission	Wide Field Planetary Camera 2 (WFPC2), a visible/ultraviolet-light camera with corrective optics to compensate for the flaw in the primary mirror	1993–present
	Corrective Optics Space Telescope Axial Replacement (COSTAR), a device that placed corrective optics over *Hubble*'s original instruments to compensate for the flawed primary mirror	1993–present (no longer in use; current instruments designed with corrected optics)
Instruments from second	Near Infrared Camera and Multi-Object Spectrometer (NICMOS),	1997–present (inoperable

servicing mission	*Hubble*'s primary camera for observing infrared light	1999–2002)
	Space Telescope Imaging Spectrograph (STIS), a much more efficient optical/UV spectrograph than the FOS or GHRS; can also be used as an optical/UV camera	1997–present (inoperable since 2004)
Instrument from fourth servicing mission	Advanced Camera for Surveys (ACS), an optical-light camera much more sensitive than WFPC2 and with a wider field of view	2002–present
Planned instruments	Cosmic Origins Spectrograph (COS), an extremely sensitive UV spectrograph	Awaiting installation
	Wide Field Camera 3 (WFC3), an advanced optical-infrared camera	Awaiting installation

*As of 2006.

History

Two disadvantages of ground-based observing were well known to early-twentieth- century astronomers: (1) Because of the turbulent motions of Earth's atmospheric gases, the paths of light rays passing through the atmosphere are constantly shifting, distorting our view of astronomical objects. To human eyes these distortions are rather subtle; for example, they are responsible for the twinkling of stars. However, this effect limits the sharpness of most images taken with ground-based telescopes to a resolution of no better than 1 arcsecond (Fig. 3). (2) The Earth's atmosphere is quite transparent to visible light but blocks much of the infrared and ultraviolet light from the cosmos. Both of these wavelengths are scientifically important. See also: Twinkling stars

In the 1920s, the decade in which the American scientist Robert Goddard launched the first liquid-fueled rockets, the German scientist Hermann Oberth published the first serious papers describing the advantages of a space-based telescope. Development of the V2 rocket in Germany during World War II made Oberth's speculations seem much more realistic. After the war, in 1946 the American astronomer Lyman Spitzer produced a detailed report for the RAND Corporation on what a large space-based telescope might accomplish. This report is widely regarded as the birth of the Hubble Space Telescope.

Even though the rationale for a space-based telescope was clear in 1946, the technology was not yet ready. Launch vehicles capable of placing a large telescope into orbit were not developed until the 1960s, when the planning of the *Hubble Space Telescope* began in earnest. Several smaller precursors, such as the *Orbiting Astronomical Observatory* (*OAO*) and the *International Ultraviolet Explorer* (*IUE*), preceded *Hubble* into space, demonstrating both the feasibility and the rewards of astronomical observing from above Earth's atmosphere. Meanwhile, NASA and the astronomy community worked to build political support for a much larger, much more expensive telescope in space. See also: Satellite (astronomy)

Congress approved the so-called Space Telescope in 1977. Lockheed Corporation was chosen to build the spacecraft, and Perkin-Elmer Corporation to grind and polish the primary mirror. The spacecraft, renamed the *Hubble Space Telescope* in 1983 in honor of American astronomer Edwin Powell *Hubble*, was ready for launch in 1986, but the tragedy of the *Challenger* space shuttle explosion delayed *Hubble*'s launch until 1990.

The space shuttle *Discovery* finally carried *Hubble* aloft on April 24, 1990, forty-four years after Spitzer's seminal report. The shuttle's robotic arm released the spacecraft into orbit the following day. However, the ultrasharp pictures expected from *Hubble* did not begin to arrive until 3½ years later.

Shortly after launch, astronomers realized that *Hubble* could not be properly focused. The source of the problem was a flaw in the primary mirror which caused an effect known as spherical aberration. *Hubble*'s mirror was exquisitely polished, but its overall shape was incorrect.

Fortunately, NASA had designed *Hubble* for periodic servicing and upgrades (see table). During the first servicing mission in December 1993, astronauts were able to install a new camera (WFPC2) with optics that corrected for the flaw in *Hubble*'s mirror, as well as a device (COSTAR) that placed corrective optics in front of *Hubble*'s original instruments. That mission also installed new solar arrays on *Hubble*, eliminating some troublesome vibrations of the spacecraft produced by the original arrays. With these improvements, *Hubble*'s performance surpassed the original specifications, enabling *Hubble* to fulfill its scientific promise (Fig. 3).

Subsequent servicing missions performed additional upgrades. The second servicing mission, in February 1997, installed two new instruments: STIS, a vastly improved spectrograph, and NICMOS, *Hubble*'s primary infrared camera. The third mission, in December 1999, replaced four of *Hubble*'s guiding gyroscopes and fixed some of *Hubble*'s multilayer insulation. The fourth mission, in March 2002, installed a state-of-the-art visible-light camera, the Advanced Camera for Surveys (ACS), a new set of solar arrays, and a cooling system that revived the NICMOS camera, which had been inoperable since 1999.

A fifth servicing mission, originally scheduled for 2005, has been delayed by the loss of the shuttle *Columbia* and ongoing problems with the Space Shuttle program. The mission will install a more sensitive spectrograph (COS) and an upgraded optical/infrared camera (WFC3), along with new batteries and gyroscopes that are essential for extending *Hubble*'s useful lifetime. Each month that passes without an upgrade now places the *Hubble* spacecraft in greater danger of an equipment failure that would prematurely end its mission.

Highlights of Hubble science

The *Hubble Space Telescope*'s contributions to astronomy are numerous and wide-ranging. The following are a few of the most notable.

Measuring the size and age of the universe

The primary method for measuring distances to other galaxies is to measure the brightness of stars whose intrinsic light outputs are known by other means. A class of stars known as Cepheid variables is particularly useful because the period over which they vary in brightness is directly related to their total light output. By comparing the apparent brightness of these stars to the total light output inferred from their brightness variations, astronomers can calculate their distance. *Hubble*'s high resolution has enabled the study of individual Cepheid variable stars in distant galaxies and the measurement of distances to galaxies up to 100 million light-years away. From the distances to these galaxies and the speeds at which they are moving away from each other, astronomers can calculate how long it took for galaxies to reach their current positions. Current estimates put this amount of time—the age of the universe—about 13.5 billion years. See also: Cepheids; Cosmology; Hubble constant

Observations of young galaxies

Hubble has supplied the first clear pictures of what the universe was like when it was only 1 or 2 billion years old. Images such as the Hubble Deep Field and Hubble Ultra Deep Field reveal a multitude of galaxies at a wide range of distances, some of them over 10 billion light-years away. Light collected from these most distant galaxies took over 10 billion years to reach Earth. Thus, the images of these galaxies show how they looked over 10 billion years ago. Many of them appear quite strange and distorted in comparison to present-day galaxies, leading astronomers to believe that disruptive collisions between galaxies were much more common early in time than they are now (**Fig. 4**). See also: Galaxy, external

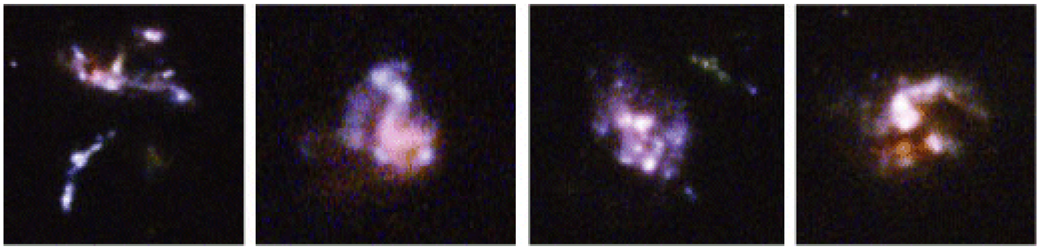

Fig. 4 Distant galaxies from the Hubble Ultra Deep Field. The distorted appearances of these galaxies suggest that they collided with other galaxies shortly before their light began the long journey to Earth.

Disks around young stars

The motions of planets in the solar system, which generally follow roughly circular paths sharing the same orbital plane, have long led astronomers to speculate that the solar system formed from a disk-shaped collection of matter with the Sun at its center. *Hubble* has helped to verify this suspicion through its observations of young stars in the process of formation. All stars, including the Sun, were born in clouds of interstellar hydrogen gas. Observations of clouds in which stars are currently forming show that brand-new stars are generally surrounded by disks of gas and tiny, solid particles called dust grains. The gas and dust in at least some of these disks are eventually expected to clump into planets similar to those that orbit the Sun.
See also: Solar system; Star; Stellar evolution

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