Space Telescopes and Observatories

(Astronomical Instruments)

Glinda Chiu

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Delhi - 110002
Email: info@wtbooks.com

Table of Contents

Chapter- 1

Compton Gamma Ray Observatory

Compton Gamma Ray Observatory

General information

NSSDC ID	1991-027B
Organization	NASA
Major contractors	TRW
Launch date	5 April 1991
Launched from	Kennedy Space Center
Launch vehicle	Space Shuttle *Atlantis* STS-37
Mission length	9 years, 2 months
Deorbited	4 June 2000
Mass	17,000 kg (37,000 lb)
Orbit height	450 km (280 mi)

Orbit period	90 min (1.5 h)
Telescope style	Scintillation detectors
Wavelength	Gamma
Diameter	N/A
Collecting area	Varies by instrument
Focal length	N/A
	Instruments
BATSE	all-sky monitor
OSSE	pointed detectors
COMPTEL	imaging telescope
EGRET	wide field telescope
Website	NASA Compton Gamma Ray Observatory

The **Compton Gamma Ray Observatory** (**CGRO**) was the second of the NASA "Great Observatories" to be launched to space, following the Hubble Space Telescope. CGRO was named after Dr. Arthur Holly Compton (Washington University in St. Louis), Nobel prize winner, for work involved with gamma ray physics. CGRO was built by TRW (now Northrop Grumman Aerospace Systems) in Redondo Beach, CA. Following 14 years of effort, the observatory was launched on the Space Shuttle *Atlantis*, mission STS-37, on 5 April 1991 and operated until its deorbit on 4 June 2000. It was deployed in low earth orbit at 450 km (280 miles) to avoid the Van Allen radiation belt. It was the heaviest astrophysical payload ever flown at that time at 17,000 kilograms (37,000 lb).

The CGRO is part of NASA's Great Observatories series, with the Hubble Space Telescope, the Chandra X-ray Observatory, and the Spitzer Space Telescope.

Instruments

CGRO carried a complement of four instruments that covered an unprecedented six decades of the electromagnetic spectrum, from 20 keV to 30 GeV. In order of increasing spectral energy coverage:

BATSE

- The **Burst and Transient Source Experiment**, (**BATSE**) by NASA's Marshall Space Flight Center searched the sky for short duration gamma ray bursts (20 to >600 keV) and conducted full sky surveys for long-lived sources. It consisted of eight identical detector modules, one at each of the satellite's corners (left, right; front and back; top and bottom). Each module consisted of both a NaI(Tl) Large Area Detector (LAD) covering the 20 keV to ~2 MeV range, 50.48 cm in dia by 1.27 cm thick, and a 12.7 cm dia by 7.62 cm thick NaI Spectroscopy Detector, which extended the upper energy range to 8 MeV, all surrounded by a plastic scintillator in active anti-coincidence to veto the large background rates due to cosmic rays and trapped radiation. Sudden increases in the LAD rates triggered a high-speed data storage mode, the details of the burst being read out to telemetry later. Bursts were typically detected at rates of roughly one per day over the 9-year CGRO mission. A strong burst could result in the observation of many thousands of gamma rays within a time interval ranging from ~0.1 s up to about 100 s.

The Compton Gamma Ray Observatory during deployment from STS-37

OSSE

- The **Oriented Scintillation Spectrometer Experiment**, (**OSSE**), by the Naval Research Laboratory detected gamma rays entering the field of view of any of four detector modules, which could be pointed individually, and were effective in the 0.05 to 10 MeV range. Each detector had a central scintillation spectrometer crystal of NaI(Tl) 12 in (303 mm) in diameter, by 4 in (102 mm) thick, optically coupled at the rear to a 3 in (76.2 mm) thick CsI(Na) crystal of similar diameter, viewed by seven photomultiplier tubes, operated as a phoswich: ie, particle and gamma-ray events from the rear produced slow-rise time (~1 μs) pulses, which could be electronically distinguished from pure NaI events from the front, which produced faster (~0.25 μs) pulses. Thus the CsI backing crystal acted as an active anticoncidence shield, vetoing events from the rear. A further barrel-shaped CsI shield, also in electronic anticoincidence, surrounded the central detector on the sides and provided coarse collimation, rejecting gamma rays and charged particles from the sides or most of the forward field-of-view (FOV). A finder level of angular collimation was provided by a tungston slat collimator grid within the outer CsI barrel, which collimated the response to a 3.8° x 11.4° FWHM rectangular FOV. A plastic scintillator across the front of each module vetoed charged particles entering from the front. The four detectors were typically operated in pairs of two. During a gamma-ray source observation, one detector would take observations of the source, while the other would slew slightly off source to measure the background levels. The two detectors would routinely switch roles, allowing for more accurate measurements of both the source and background. The instruments could slew with a speed of approximately 2 degrees per second.

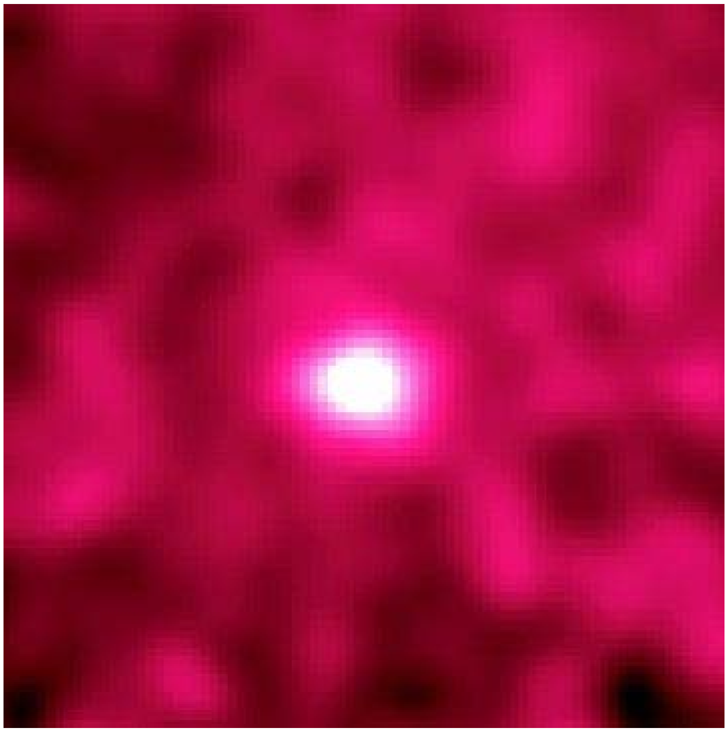
COMPTEL

- The **Imaging Compton Telescope**, (**COMPTEL**) by the Max Planck Institute for Extraterrestrial Physics, the University of New Hampshire, Netherlands Institute for Space Research, and ESA's Astrophysics Division was tuned to the 0.75-30 MeV energy range and determined the angle of arrival of photons to within a degree and the energy to within five percent at higher energies. The instrument had a field of view of one steradian. For cosmic gamma-ray events, the experiment required two nearly simultaneous interactions, in a set of front and rear scintillators. Gamma rays would Compton scatter in a forward detector module, where the interaction energy E_1, given to the recoil electron was measured, while the Compton scattered photon would then be caught in one of a second layer of scintillators to the rear, where its total energy, E_2, would be measured. From these two energies, E_1 and E_2, the Compton scattering angle, angle θ, can be determined, along with the total energy, $E_1 + E_2$, of the incident photon. The positions of the interactions, in both the front and rear scintillators, was also measured. The vector, **V**, connecting the two interaction points determined a direction to the sky, and the angle θ about this direction, defined a cone about **V** on which the source of the photon must lie, and a corresponding "event circle" on the sky. Because of the requirement for a near coincidence between the two interactions, with the correct delay of a few nanoseconds, most modes of background production were strongly suppressed. From the collection of many event energies and event circles, a map of the positions of sources, along with their photon fluxes and spectra, could be determined.

EGRET

- The **Energetic Gamma Ray Experiment Telescope**, (**EGRET**) measured high energy (20 MeV to 30 GeV) gamma ray source positions to a fraction of a degree and photon energy to within 15 percent. EGRET was developed by NASA Goddard Space Flight Center, the Max Planck Institute for Extraterrestrial Physics, and Stanford University. Its detector operated on the principle of electron-positron pair production from high energy photons interacting in the detector. The tracks of the high-energy electron and positron created were measured within the detector volume,and the axis of the *V* of the two emerging particles projected to the sky. Finally, their total energy was measured in a large calorimeter scintillation detector at the rear of the instrument.

Results



The Moon as seen by the Compton Gamma Ray Observatory, in gamma rays of greater than 20 MeV. These are produced by cosmic ray bombardment of its surface. The Sun, which has no similar surface of high atomic number to act as target for cosmic rays, cannot be seen at all at these energies, which are too high to emerge from primary nuclear reactions, such as solar nuclear fusion.

Basic results

- The EGRET instrument conducted the first all sky survey above 100 MeV. Using four years of data it discovered 271 sources, 170 of which were unidentified.
- The COMPTEL instrument completed an all sky map of ^{26}Al (a radioactive isotope of aluminum).
- The OSSE instrument completed the most comprehensive survey of the galactic center, and discovered a possible antimatter "cloud" above the center.
- The BATSE instrument averaged one gamma ray burst event detection per day for a total of approximately 2700 detections. It definitively showed that the majority of gamma-ray bursts must originate in distant galaxies, not nearby in our own Milky Way, and therefore must be enormously energetic.
- The discovery of the first four soft gamma ray repeaters; these sources were relatively weak, mostly below 100 keV and had unpredictable periods of activity and inactivity
- The separation of GRBs into two time profiles: short duration GRBs that last less than 2 seconds, and long duration GRBs that last longer than this.

GRB 990123

Gamma ray burst 990123 (23 January 1999) was one of the brightest bursts recorded at the time, and was the first GRB with an optical afterglow observed during the prompt gamma ray emission (a reverse shock flash). This allowed astronomers to measure a redshift of 1.6 and a distance of 4.5 Gpc (15 Gly). Combining the measured energy of the burst in gamma-rays and the distance, the total emitted energy assuming an isotropic explosion could be deduced and resulted in the direct conversion of approximately two solar masses into energy. This finally convinced the community that GRB afterglows resulted from highly collimated explosions, which strongly reduced the needed energy budget.

Miscellaneous results

- The completion of both a pulsar survey and a supernova remnant survey
- The discovery of terrestrial gamma ray sources in 1994 that came from thunderclouds

De-orbit

After one of its gyroscopes failed, the observatory was deliberately de-orbited. At the time, the observatory was still operational, however the failure of another gyroscope would have made de-orbiting much more difficult and dangerous. With some controversy, NASA decided in the interest of public safety that a controlled crash was preferable to letting the craft come down on its own at random. Unlike the Hubble Space Telescope, it was not designed for on-orbit repair and refurbishment. It entered the Earth's atmosphere on 4 June 2000, with the debris that did not burn up falling harmlessly into the Pacific Ocean.

Chapter- 2

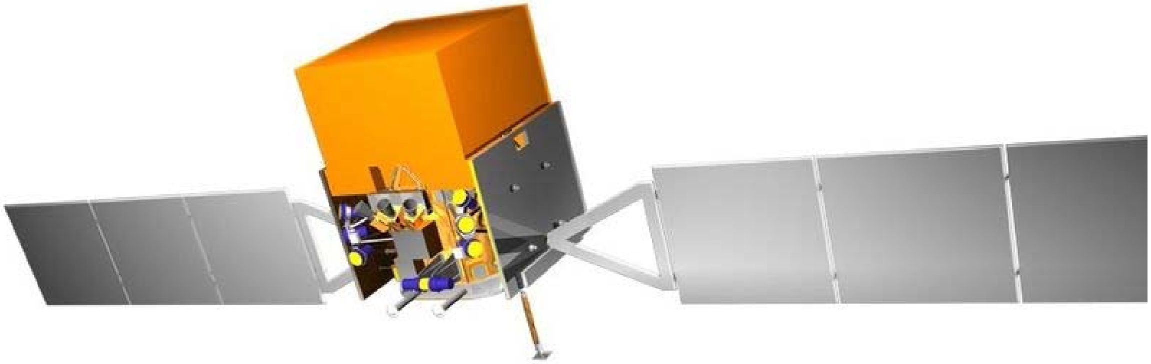
Fermi Gamma-Ray Space Telescope

Fermi Gamma-ray Space Telescope

General information

NSSDC ID	2008-029A
Organization	NASA, United States Department of Energy, and government agencies in France, Germany, Italy, Japan, and Sweden.
Major contractors	General Dynamics
Launch date	2008-06-11 16:05 UTC
Launched	Space Launch Complex 17-B Cape

from	Canaveral Air Force Station
Launch vehicle	Delta II 7920-H
Mission length	elapsed: 2 years, 7 months, and 23 days
Orbit height	550 km (340 mi)
Orbit period	~ 95 minutes
Wavelength	gamma ray
	Instruments
LAT	Large Area Telescope
GBM	Gamma-ray Burst Monitor



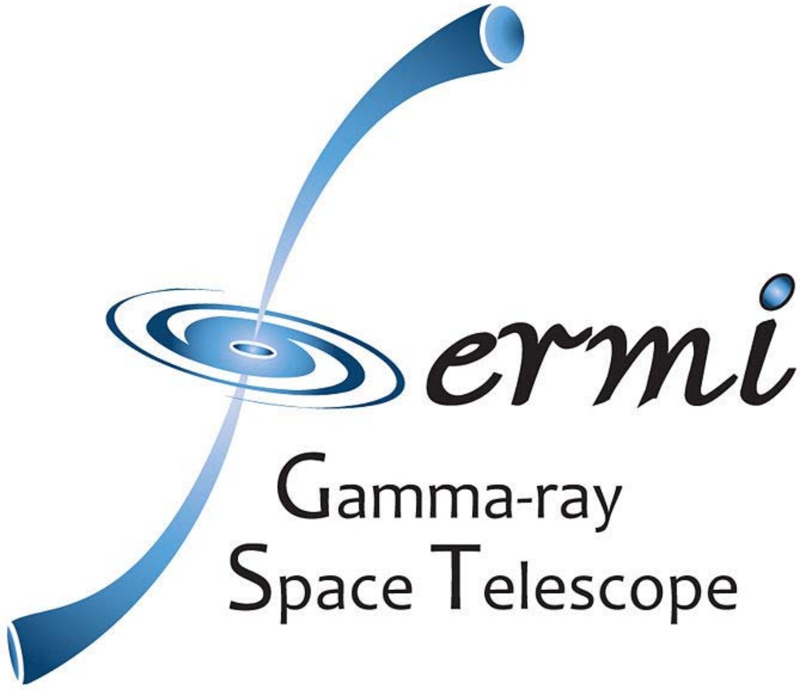
Artist's conception of Fermi in orbit

The **Fermi Gamma-ray Space Telescope (FGST)**, formerly referred to as the "Gamma-ray Large Area Space Telescope (GLAST)," is a space observatory being used to perform gamma-ray astronomy observations from low Earth orbit. Its main instrument is the Large Area Telescope (LAT), with which astronomers mostly intend to perform an all-sky survey studying astrophysical and cosmological phenomena such as active galactic nuclei, pulsars, other high-energy sources and dark matter. Another instrument aboard Fermi, the Gamma-ray Burst Monitor (GBM; formerly GLAST Burst Monitor), is being used to study gamma-ray bursts.

FGST was launched on 11 June 2008 at 16:05 GMT aboard a Delta II 7920-H rocket. The mission is a joint venture of NASA, the United States Department of Energy, and government agencies in France, Germany, Italy, Japan, and Sweden.

Overview

Fermi includes two scientific instruments, the Large Area Telescope (LAT) and the Gamma-ray Burst Monitor (GBM). The LAT is an imaging gamma-ray detector (a pair-conversion instrument) which detects photons with energy from about 30 million to about 300 billion electron volts (30 MeV - 300 GeV), with a field of view of about 20% of the sky; it may be thought of as a sequel to the EGRET instrument on the Compton gamma ray observatory. The GBM consists of 14 scintillation detectors (twelve sodium iodide crystals for the 8keV to 1MeV range and two bismuth germanate crystals with sensitivity from 150keV to 30MeV), and can detect gamma-ray bursts in that energy range across the whole of the sky not occluded by the Earth.



Fermi G.S.T. logo

General Dynamics Advanced Information Systems (formerly Spectrum Astro and now Orbital Sciences) in Gilbert, Arizona designed and built the spacecraft that carries the instruments. It travels in a low, circular orbit with a period of about 95 minutes. Its normal mode of operation maintains its orientation so that the instruments will look away from the earth, with a "rocking" motion to equalize the coverage of the sky. The view of the instruments will sweep out across most of the sky about 16 times per day. The spacecraft can also maintain an orientation that points to a chosen target.

Both science instruments underwent environmental testing, including vibration, vacuum, and high and low temperatures to ensure that they can withstand the stresses of launch and continue to operate in space. They were integrated with the spacecraft at the General Dynamics ASCENT facility in Gilbert, Arizona.

Data from the instruments will be available to the public through the Fermi Science Support Center web site. Software for analyzing the data will also be available. Scientists with plans for research will be able to apply to the Guest Investigator program.

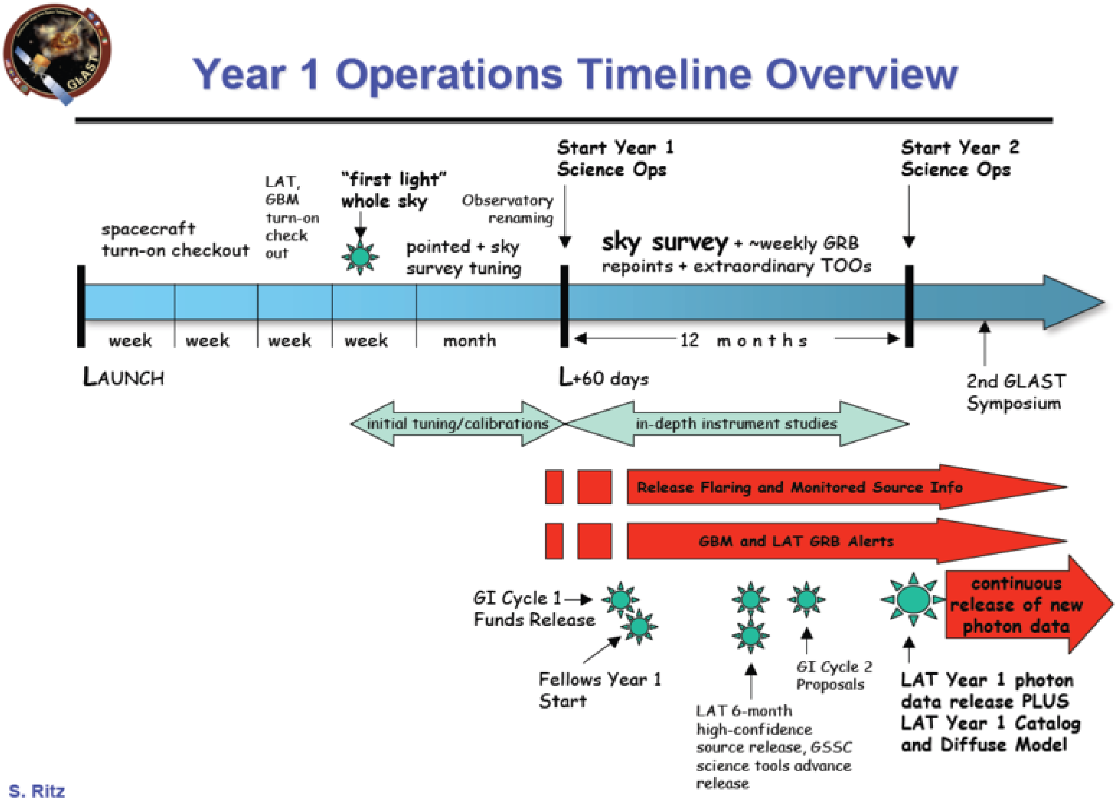
GLAST renamed FGST

Fermi gained its new name in 2008.

NASA's Alan Stern, associate administrator for Science at NASA Headquarters, launched a public competition 7 Feb 2008, closing 31 Mar 2008, to rename GLAST in a way that would "capture the excitement of GLAST's mission and call attention to gamma-ray and high-energy astronomy... something memorable to commemorate this spectacular new astronomy mission... a name that is catchy, easy to say and will help make the satellite and its mission a topic of dinner table and classroom discussion."

On 26 Aug 2008, GLAST was renamed the "Fermi Gamma-ray Space Telescope" in honor of Enrico Fermi, a pioneer in high-energy physics.

Mission



Anticipated operations timeline

The GLAST instrument after arriving at Cape Canaveral in May 2008

NASA designed the mission with a five-year lifetime, with a goal of ten years of operations.

The key scientific objectives of the Fermi mission have been described as:

- To understand the mechanisms of particle acceleration in active galactic nuclei (AGN), pulsars, and supernova remnants (SNR).
- Resolve the gamma-ray sky: unidentified sources and diffuse emission.
- Determine the high-energy behavior of gamma-ray bursts and transients.
- Probe dark matter (e.g. by looking for an excess of gamma rays from the center of the Milky Way) and early Universe.

- Search for evaporating primordial micro black holes (MBH) from their presumed gamma burst signatures [Hawking Radiation component].

The National Academies of Sciences ranked this mission as a top priority. Many new possibilities and discoveries are anticipated to emerge from this single mission and greatly expand our view of the Universe.

- Blazars and active galaxies

  Study energy spectra and variability of wavelengths of light coming from blazars so as to determine the composition of the black hole jets aimed directly at Earth -- whether they are
  (a) a combination of electrons and positrons or
  (b) only protons.

- Gamma-ray bursts

  Study gamma-ray bursts with an energy range several times more intense than ever before so that scientists may be able to understand them better.

- Neutron stars

  Study younger, more energetic pulsars in the Milky Way than ever before so as to broaden our understanding of stars. Study the pulsed emissions of magnetospheres so as to possibly solve how they are produced. Study how pulsars generate winds of interstellar particles.

- Milky Way galaxy

  Provide new data to help improve upon existing theoretical models of our own galaxy.

- Gamma-ray background radiation

  Study better than ever before whether ordinary galaxies are responsible for gamma-ray background radiation. The potential for a tremendous discovery awaits if ordinary sources are determined to be irresponsible, in which case the cause may be anything from self-annihilating dark matter to entirely new chain reactions among intersellar particles that have yet to be conceived.

- The early universe

  Study better than ever before how concentrations of visible and ultraviolet light change over time. The mission should easily detect $E=mc^2$ working in reverse, where energy was actually converted into mass, in the early universe.

- Sun

  Study better than ever before how our own Sun produces gamma rays in solar flares.

- Dark matter

  Search for evidence that dark matter is made up of weakly interacting massive particles, complementing similar experiments already planned for the Large Hadron Collider as well as other underground detectors. The potential for a tremendous discovery in this area is possible over the next several years.

- Fundamental physics

  Test better than ever before certain established theories of physics, such as whether the speed of light in vacuum remains constant regardless of wavelength. Einstein's general theory of relativity contends that it does, yet some models in quantum mechanics and quantum gravity predict that it may not. Search for gamma rays emanating from former black holes that once exploded, providing yet another potential step toward the unification of quantum mechanics and general relativity. Determine whether photons naturally split into smaller photons, as predicted by quantum mechanics and already achieved under controlled, man-made experimental conditions.

- Unknown discoveries

  Scientists estimate a very high possibility for new scientific discoveries, even revolutionary discoveries, emerging from this single mission.

Mission status

Prelaunch

On 4 Mar 2008 the spacecraft arrived at the Astrotech payload processing facility in Titusville, Florida. On 4 Jun 2008, after several previous delays, launch status was retargeted for June 11 at the earliest, the last delays resulting from the need to replace the Flight Termination System batteries. The launch window extended from 11:45 a.m. until 1:40 p.m. EDT (15:45-17:40 GMT) daily, until 7 Aug 2008.

Launch

GLAST launch aboard a Delta II rocket, 11 June 2008.

Launch occurred successfully on 11 Jun 2008 at 16:05, and the spacecraft separated from the carrier rocket about 75 minutes later. The spacecraft departed from pad B at Cape Canaveral Air Force Station Space Launch Complex 17 aboard a Delta 7920H-10C rocket.

Orbit

Fermi resides in a low-earth circular orbit at an altitude of 550 km (340 mi), and at an inclination of 28.5 degrees.

Software modifications

GLAST received some minor modifications to its computer software 2008-06-23.

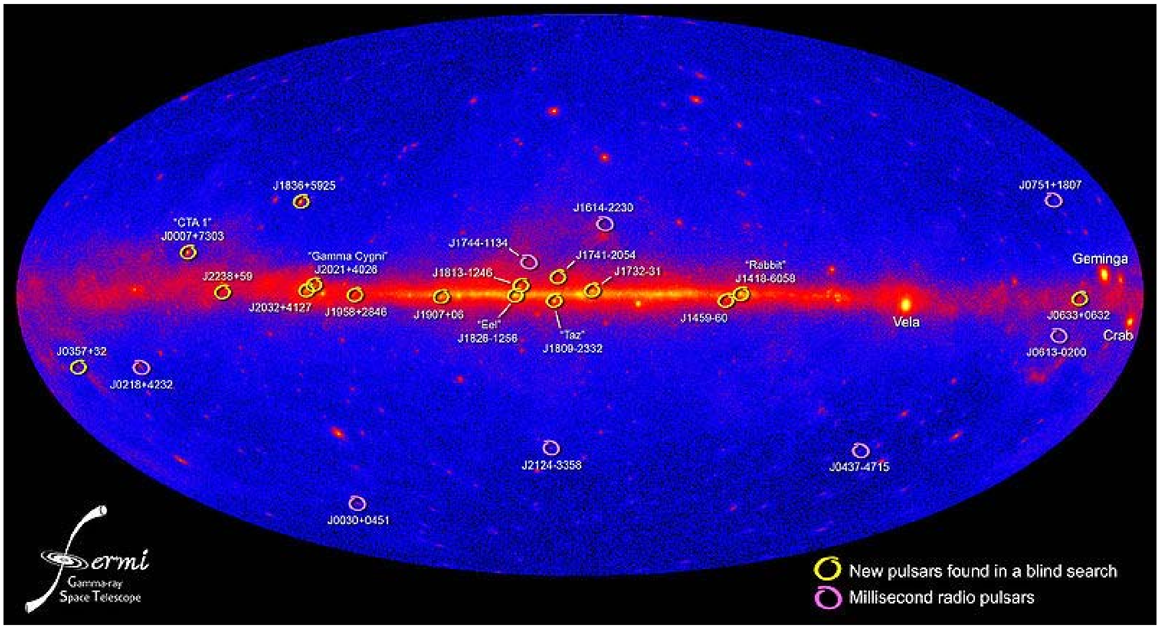
LAT/GBM computers operational

Computers operating both the LAT and GBM and most of the LAT's components were turned on, 2008-06-24. The LAT high voltage was turned on, 2008-06-25, and it began detecting high-energy particles from space, but minor adjustments were still needed to calibrate the instrument. The GBM high voltage was also turned on, 2008-06-25, but the GBM still required one more week of testing/calibrations before searching for gamma-ray bursts.

Sky survey mode

After presenting an overview of the Fermi instrumentation and goals, Jennifer Carson of SLAC National Accelerator Laboratory had concluded that the primary goals were "all achievable with the all-sky scanning mode of observing." Fermi switched to "sky survey mode" on 26 June 2008 so as to begin sweeping its field of view over the entire sky every three hours (every two orbits).

Discoveries



Gamma-ray pulsars detected by the Fermi Gamma-ray Space Telescope

Cycle of pulsed gamma rays from the Vela pulsar. Constructed from photons detected by Fermi's Large Area Telescope.

Pulsar discovery

The first major discovery came when the space telescope detected a pulsar in the CTA 1 supernova remnant that appeared to emit radiation in the gamma ray bands only, a first for its kind. This new pulsar sweeps the earth every 316.86 milliseconds and is about 4,600 light years away.

Greatest GRB energy release

In September 2008, the gamma-ray burst GRB 080916C in the constellation Carina was recorded by the Fermi telescope. This burst is notable as having "the largest apparent energy release yet measured." The explosion had the power of about 9,000 ordinary supernovae, and the relativistic jet of material ejected in the blast must have moved at a minimum of 99.9999% the speed of light. Overall, GRB 080916C had "the greatest total energy, the fastest motions, and the highest-energy initial emissions" ever seen.

Cosmic rays and supernova remnants

In February 2010, it was announced that FGST had determined that supernova remnants act as enormous accelerators for cosmic particles. This determination fulfills one of the stated missions for this project.

Background gamma ray sources

In March 2010 it was announced that active galactic nuclei are not responsible for most gamma-ray background radiation. Though active galactic nuclei do produce some of the gamma-ray radiation detected here on Earth, less than 30% originates from these sources. The search now is to locate the sources for the remaining 70% or so of all gamma-rays detected. Possibilities include star forming galaxies, galactic mergers, and yet-to-be explained dark matter interactions.

Fermi bubbles

In November 2010, it was announced two gamma-ray & x-ray bubbles were detected around Earth's galaxy, the Milky way. The bubbles extend about 25 thousand light years distant above and below the center of the galaxy. The galaxy's diffuse gamma-ray fog hampered prior observations, but the discovery team lead by D. Finkbeiner, building on research by G. Dobler, worked around this problem.

Fermi science packages

Gamma-ray Burst Monitor (GBM)

The Gamma-ray Burst Monitor (GBM) (formerly GLAST Burst Monitor) detects sudden flares of gamma-rays produced by gamma ray bursts and solar flares. Its scintillators are on the sides of the spacecraft to view all of the sky which is not blocked by the earth. The design is optimized for good resolution in time and photon energy.

"Gamma-ray bursts are so bright we can see them from billions of light years away, which means they occurred billions of years ago, and we see them as they looked then," stated Charles Meegan of NASA's Marshall Space Flight Center.

The Gamma-ray Burst Monitor has detected gamma rays from positrons generated in powerful thunderstorms.

GBM participating institutions

US team institution

- NASA's Marshall Space Flight Center, University of Alabama in Huntsville

German team institutions

- Max Planck Institut für Extraterrestrische Physik

Large Area Telescope (LAT)

The Large Area Telescope (LAT) detects individual gamma rays using technology similar to that used in terrestrial particle accelerators. Photons hit thin metal sheets, converting to electron-positron pairs, via a process known as pair production. These charged particles pass through interleaved layers of silicon microstrip detectors, causing ionization which produce detectable tiny pulses of electric charge. Researchers can combine information from several layers of this tracker to determine the path of the particles. After passing through the tracker, the particles enter the calorimeter, which consists of a stack of caesium iodide scintillator crystals to measure the total energy of the particles. The LAT's field of view is large, about 20% of the sky. The resolution of its images is modest by astronomical standards, a few arc minutes for the highest-energy photons and about 3 degrees at 100 MeV. The LAT is a bigger and better successor to the EGRET instrument on NASA's Compton Gamma Ray Observatory satellite in the 1990s. Several countries produced the components of the LAT, who then sent the components for assembly at SLAC National Accelerator Laboratory.

LAT participating institutions

US team institutions

- Stanford University, Physics Department, Fermi group & Hansen Experimental Physics Laboratory
- SLAC National Accelerator Laboratory, Particle Astrophysics group
- NASA Goddard Space Flight Center, Astrophysics Science Division
- U.S. Naval Research Laboratory, High Energy Space Environment (HESE) branch
- Ohio State University, Physics Department
- University of California, Santa Cruz, Physics Department and Institute for Particle Physics
- Sonoma State University, Department of Physics & Astronomy
- University of Washington
- Texas A&M University-Kingsville

German team institutions

- Ruhr-Universität Bochum, Theoretische Physik IV: Theoretische Weltraum- und Astrophysik

Japanese team institutions

- Japan Fermi Collaboration
- University of Tokyo
- Tokyo Institute of Technology
- Institute for Cosmic Ray Research
- Institute for Space and Astronautical Science
- Hiroshima University

Italian team institutions

- Istituto Nazionale di Fisica Nucleare (INFN)
- Italian Space Agency
- Istituto di Fisica Cosmica, Milano, CNR
- INFN and University of Bari
- INFN and University of Padova
- INFN and University of Perugia
- INFN and University of Pisa
- INFN and University of Rome Tor Vergata
- INFN and University of Trieste

- INFN and University of Udine

French team institutions

- Service d'Astrophysique, CEA DAPNIA, CEA Saclay
- Centre National d'Études Spatiales
- Institut National de Physique Nucléaire et de Physique des Particules, IN2P3
- Laboratoire Leprince-Ringuet de l'École Polytechnique
- Centre d'Études nucléaires de Bordeaux Gradignan
- Laboratoire de Physique Théorique et Astroparticules, Montpellier

Swedish team institutions

- Royal Institute of Technology
- Stockholm University

Education and public outreach

Education and public outreach are important components of the Fermi project. NASA’s Education and Public Outreach (E/PO) group operates the Fermi education and outreach resources at Sonoma State University.

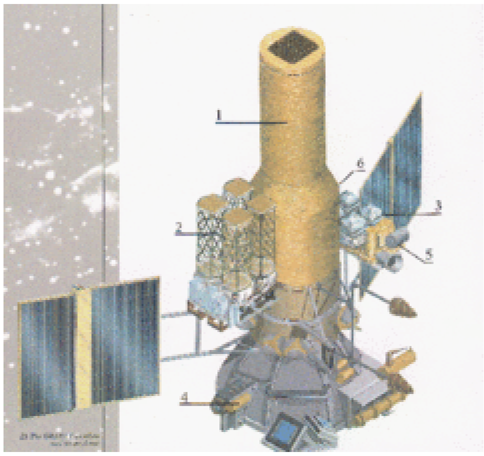
Rossi Prize

The 2011 Bruno Rossi Prize was awarded to Bill Atwood, Peter Michelson and the Fermi LAT team "for enabling, through the development of the Large Area Telescope, new insights into neutron stars, supernova remnants, cosmic rays, binary systems, active galactic nuclei and gamma-ray bursts."

Chapter- 3

Granat

International Astrophysical Observatory "GRANAT"



picture credit: NASA

General information

NSSDC ID	1989-096A
Organization	Soviet space program
Major contractors	NPO Lavochkin
Launch date	1 December 1989
Launched from	Baikonur Cosmodrome (LC200/40)
Launch vehicle	Proton rocket
Mission length	9 years
Deorbited	May 25, 1999
Mass	4 metric tons

	(experiments 2.3 metric tons)
Type of orbit	Highly elliptical
Orbit height	apogee 200,000 km perigee 2,000 km (initial values)
Orbit period	4 days
Location	Geocentric orbit
Telescope style	coded mask (SIGMA) coded mask (ART-P)
Wavelength	X-ray to gamma ray
Collecting area	800 cm^2 (SIGMA)
Instruments	
SIGMA	X-ray/gamma-ray telescope
ART-P	X-ray telescope
ART-S	X-ray spectrometer
PHEBUS	Gamma-burst detector
WATCH	All-sky monitor
KONUS-B **TOURNESOL**	Gamma-ray burst experiments

The **International Astrophysical Observatory "GRANAT"** (usually known as **Granat**; Russian: Гранат), was a Soviet (later Russian) space observatory developed in collaboration with France, Denmark and Bulgaria. It was launched on 1 December 1989 aboard a Proton rocket and placed in a highly eccentric four-day orbit, of which three were devoted to observations. It operated for almost nine years.

In September 1994, after nearly five years of directed observations, the gas supply for its attitude control was exhausted and the observatory was placed in a non-directed survey mode. Transmissions finally ceased on 27 November 1998.

With seven different instruments on board, Granat was designed to observe the universe at energies ranging from X-ray to gamma ray. Its main instrument, SIGMA, was capable of imaging both hard X-ray and soft gamma-ray sources. The PHEBUS instrument was meant to study gamma-ray bursts and other transient X-Ray sources. Other experiments such as ART-P were intended to image X-Ray sources in the 35 to 100 keV range. One instrument, WATCH, was designed to monitor the sky continuously and alert the other instruments to new or interesting X-Ray sources. The ART-S spectrometer covered the X-ray energy range while the KONUS-B and TOURNESOL experiments covered both the X-ray and gamma ray spectrum.

Spacecraft

Granat was a three-axis-stabilized spacecraft and the last of the Venera-class spacecraft produced by the Lavochkin Scientific Production Association. It was similar to the Astron observatory which was functional from 1983 to 1989; for this reason, the spacecraft was originally known as the Astron 2. It weighed 4.4 metric tons and carried almost 2.3 metric tons of international scientific instrumentation. Granat stood 6.5 m tall and had a total span of 8.5 m across its solar arrays. The power made available to the scientific instruments was approximately 400 W.

Launch and orbit

Proton launch vehicle carrying Granat

The spacecraft was launched on 1 December 1989 aboard a Proton rocket from the Baikonur Cosmodrome in Kazakh SSR. It was placed in a highly eccentric 98-hour orbit with an initial apogee/perigee of 200,000 km/2,000 km respectively and an inclination of 51.5 degrees. This meant that solar and lunar perturbations would significantly increase the orbits inclination while reducing its eccentricity, such that the orbit had become near-circular by the time Granat completed its directed observations in September 1994. (By 1991, the perigee had increased to 20,000 km; by September 1994, the apogee/perigee was 59,025 km / 144,550 km at an inclination of 86.7 degrees.)

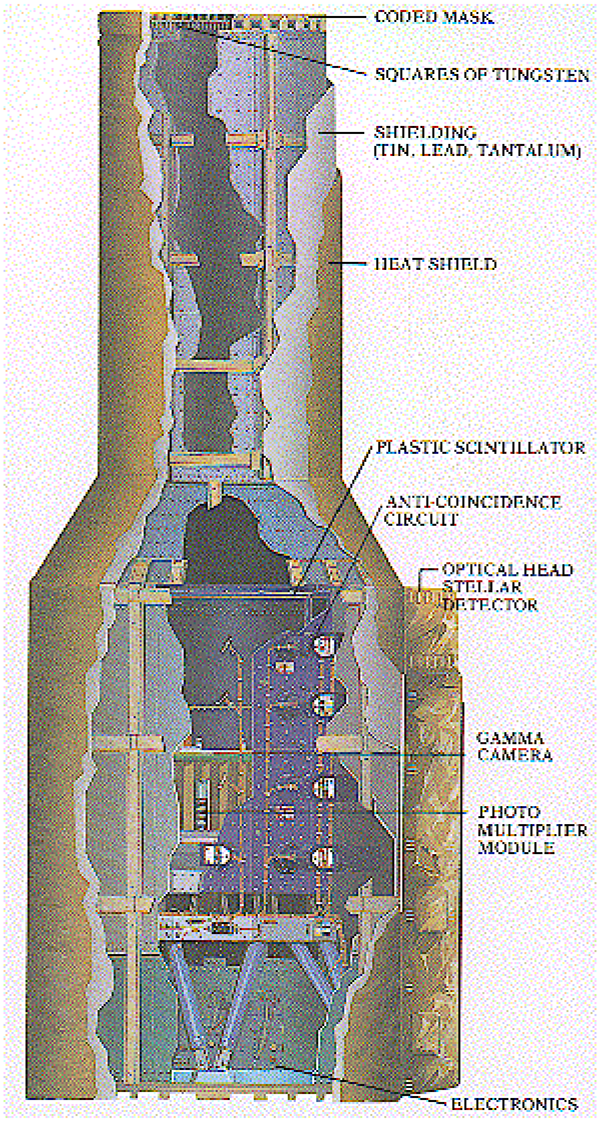
Three days out of the four-day orbit were devoted to observations. After over nine years in orbit, the observatory finally reentered the Earth's atmosphere on May 25, 1999.

Granat observatory orbit change (1994 predictions)

Date	Perigee (km)	Apogee (km)	Arg.perigee (deg)	Inc. (deg)	Long.asc.node (deg)
December 1, 1989	2,000	200,000	285	51.5	20.0
December 1, 1991	23,893	179,376	311.9	82.6	320.3
December 1, 1994	58,959	144,214	343.0	86.5	306.9
December 1, 1996	42,088.8	160,888	9.6	93.4	302.2

Instrumentation

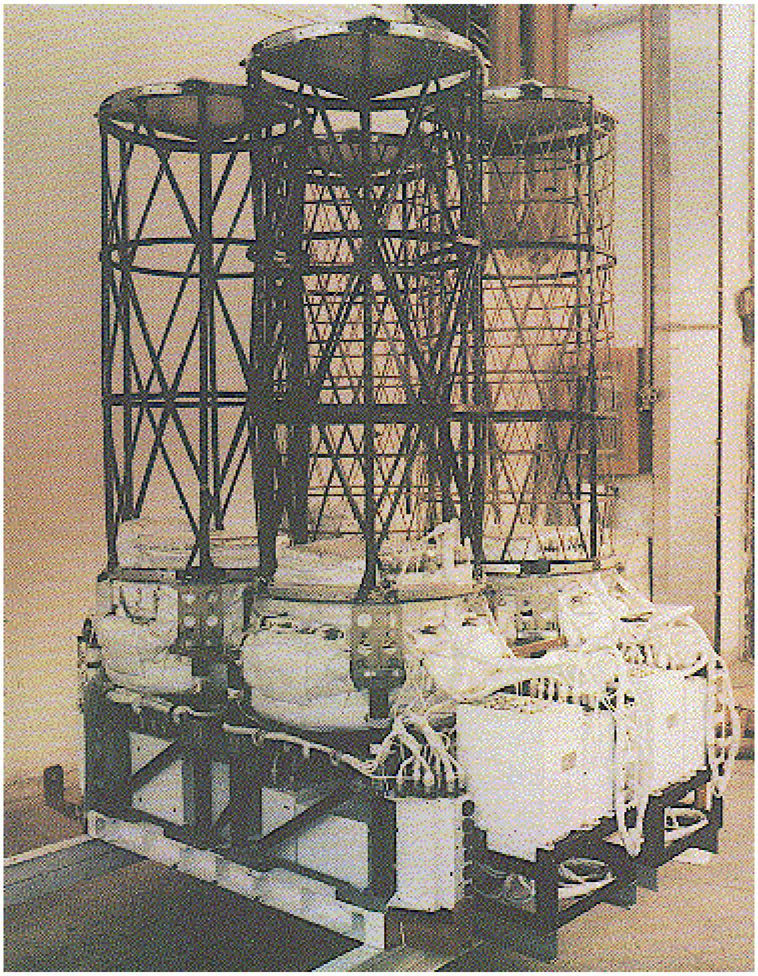
SIGMA



SIGMA instrument

The hard X-ray and low-energy gamma-ray SIGMA telescope was a collaboration between CESR (Toulouse) and CEA (Saclay). It covered the energy range 35–1300 keV, with an effective area of 800 cm^2 and a maximum sensitivity field of view of ~5°×5°. The maximum angular resolution was 15 arcmin. The energy resolution was 8% at 511 keV. Its imaging capabilities were derived from the association of a coded mask and a position sensitive detector based on the Anger camera principle.

ART-P



ART-P instrument

The ART-P X-ray telescope was the responsibility of the IKI in Moscow. The instrument covered the energy range 4 to 60 keV for imaging and 4 to 100 keV for spectroscopy and timing. There were four identical modules of the ART-P telescope, each consisting of a position sensitive multi-wire proportional counter (MWPC) together with a URA coded mask. Each module had an effective area of approximately 600 cm^2, producing a field of view of 1.8° by 1.8°. The angular resolution was 5 arcmin; temporal and energy resolutions were 3.9 ms and 22% at 6 keV, respectively. The instrument achieved a sensitivity of 0.001 of the Crab nebula source (= 1 "mCrab") in an eight-hour exposure. The maximum time resolution was 4 ms.

ART-S

The ART-S X-ray spectrometer, also built by the IKI, covered the energy range 3 to 100 keV. Its field of view was 2° by 2°. The instrument consisted of four detectors based on spectroscopic MWPCs, making an effective area of 2,400 cm² at 10 keV and 800 cm² at 100 keV. The time resolution was 200 microseconds.

PHEBUS

The PHEBUS experiment was designed by CESR (Toulouse) to record high energy transient events in the range 100 keV to 100 MeV. It consisted of two independent detectors and their associated electronics. Each detector consisted of a bismuth germinate (BGO) crystal 78 mm in diameter by 120 mm thick, surrounded by a plastic anti-coincidence jacket. The two detectors were arranged on the spacecraft so as to observe 4π steradians. The burst mode was triggered when the count rate in the 0.1 to 1.5 MeV energy range exceeded the background level by 8 sigma in either 0.25 or 1.0 seconds. There were 116 energy channels.

WATCH

Starting in January 1990, four WATCH instruments, designed by the Danish Space Research Institute, were in operation on the Granat observatory. The instruments could localize bright sources in the 6 to 180 keV range to within 0.5° using a Rotation Modulation Collimator. Taken together, the instruments' three fields of view covered approximately 75% of the sky. The energy resolution was 30% FWHM at 60 keV. During quiet periods, count rates in two energy bands (6 to 15 and 15 to 180 keV) were accumulated for 4, 8, or 16 seconds, depending on onboard computer memory availability. During a burst or transient event, count rates were accumulated with a time resolution of 1 second per 36 energy channels.

KONUS-B

The KONUS-B instrument, designed by the Ioffe Physico-Technical Institute in St. Petersburg, consisted of seven detectors distributed around the spacecraft that responded to photons of 10 keV to 8 MeV energy. They consisted of NaI(Tl) scintillator crystals 200 mm in diameter by 50 mm thick behind a Be entrance window. The side surfaces were protected by a 5 mm thick lead layer. The burst detection threshold was 500 to 50 microjoules per square meter (5×10^{-7} to 5×10^{-8} erg/cm²), depending on the burst spectrum and rise time. Spectra were taken in two 31-channel pulse height analyzers (PHAs), of which the first eight were measured with 1/16 s time resolution and the remaining with variable time resolutions depending on the count rate. The range of resolutions covered 0.25 to 8 s.

The KONUS-B instrument operated from 11 December 1989 until 20 February 1990. Over that period, the "on" time for the experiment was 27 days. Some 60 solar flares and 19 cosmic gamma-ray bursts were detected.

TOURNESOL

The French TOURNESOL instrument consisted of four proportional counters and two optical detectors. The proportional counters detected photons between 2 keV and 20 MeV in a 6° by 6° field of view. The visible detectors had a field of view of 5° by 5°. The instrument was designed to look for optical counterparts of high-energy burst sources, as well as performing spectral analysis of the high-energy events.

Science results

Over the initial four years of directed observations, Granat observed many galactic and extra-galactic X-ray sources with emphasis on the deep imaging and spectroscopy of the galactic center, broad-band observations of black hole candidates, and X-ray novae. After 1994, the observatory was switched to survey mode and carried out a sensitive all-sky survey in the 40 to 200 keV energy band.

Some of the highlights included:

- A very deep imaging (more than 5 million seconds duration) of the galactic center region.
- Discovery of electron-positron annihilation lines from the galactic microquasar 1E1740-294 and the X-ray Nova Muscae.
- Study of spectra and time variability of black hole candidates.
- Across eight years of observations, Granat discovered some twenty new X-ray sources, i.e. candidate black holes and neutron stars. Consequently, their designations begin with "GRS" meaning "GRANAT source". Examples are GRS 1915+105 (the first microquasar discovered in our galaxy) and GRS 1124-683.

Impact of the dissolution of the Soviet Union

After the end of the Soviet Union, two problems arose for the project. The first was geopolitical in nature: the main spacecraft control center was located at the Yevpatoria facility in the Crimea region. This control center was significant in the Soviet space program, being one of only two in the country equipped with a 70 m dish antenna. With the break up of the Union, the Crimea region, although mostly populated by ethnic Russians, found itself part of the newly independent Ukraine and the center was put under Ukrainian national control, prompting new political hurdles.

The main and most urgent problem, however, was in finding funds to support the continued operation of the spacecraft amid the spending crunch in post-Soviet Russia. The French space agency, having already contributed significantly to the project (both scientifically and financially), took upon itself to fund the continuing operations directly.

Chapter- 4

Chandra X-Ray Observatory

Chandra X-ray Observatory

Chandra X-ray Observatory and Inertial Upper Stage sit inside the payload bay on Space Shuttle *Columbia* mission STS-93

General information

NSSDC ID	1999-040B
Organization	NASA, SAO, CXC
Major contractors	TRW, Northrop Grumman
Launch date	23 July 1999
Launched from	Kennedy Space Center
Launch vehicle	Space Shuttle *Columbia* STS-93
Mission length	planned: 5 years elapsed: 11 years, 6 months, and 12 days
Mass	4,790 kg (10,600 lb)
Orbit height	apogee 133,000 km (83,000 mi) perigee 16,000 km (9,900 mi)
Orbit period	64.2 hours
Wavelength	X-ray (0.1 - 10 keV)
Diameter	1.2 m (3.9 ft)
Collecting area	0.04 m^2 (0.43 sq ft) at 1 keV
Focal length	10 m (33 ft)

The **Chandra X-ray Observatory** is a satellite launched on STS-93 by NASA on July 23, 1999. It was named in honor of Indian-American physicist Subrahmanyan Chandrasekhar who is known for determining the maximum mass for white dwarfs. "Chandra" also means "moon" or "luminous" in Sanskrit.

Chandra Observatory is the third of NASA's four Great Observatories. The first was Hubble Space Telescope; second the Compton Gamma Ray Observatory, launched in 1991; and last is the Spitzer Space Telescope. Prior to successful launch, the Chandra Observatory was known as AXAF, the Advanced X-ray Astrophysics Facility. AXAF was assembled and tested by TRW (now Northrop Grumman Space Technology) in Redondo Beach, California. Chandra is sensitive to X-ray sources 100 times fainter than any previous X-ray telescope, due primarily to the high angular resolution of the Chandra mirrors.

Since the Earth's atmosphere absorbs the vast majority of X-rays, they are not detectable from Earth-based telescopes, requiring a space-based telescope to make these observations.

History

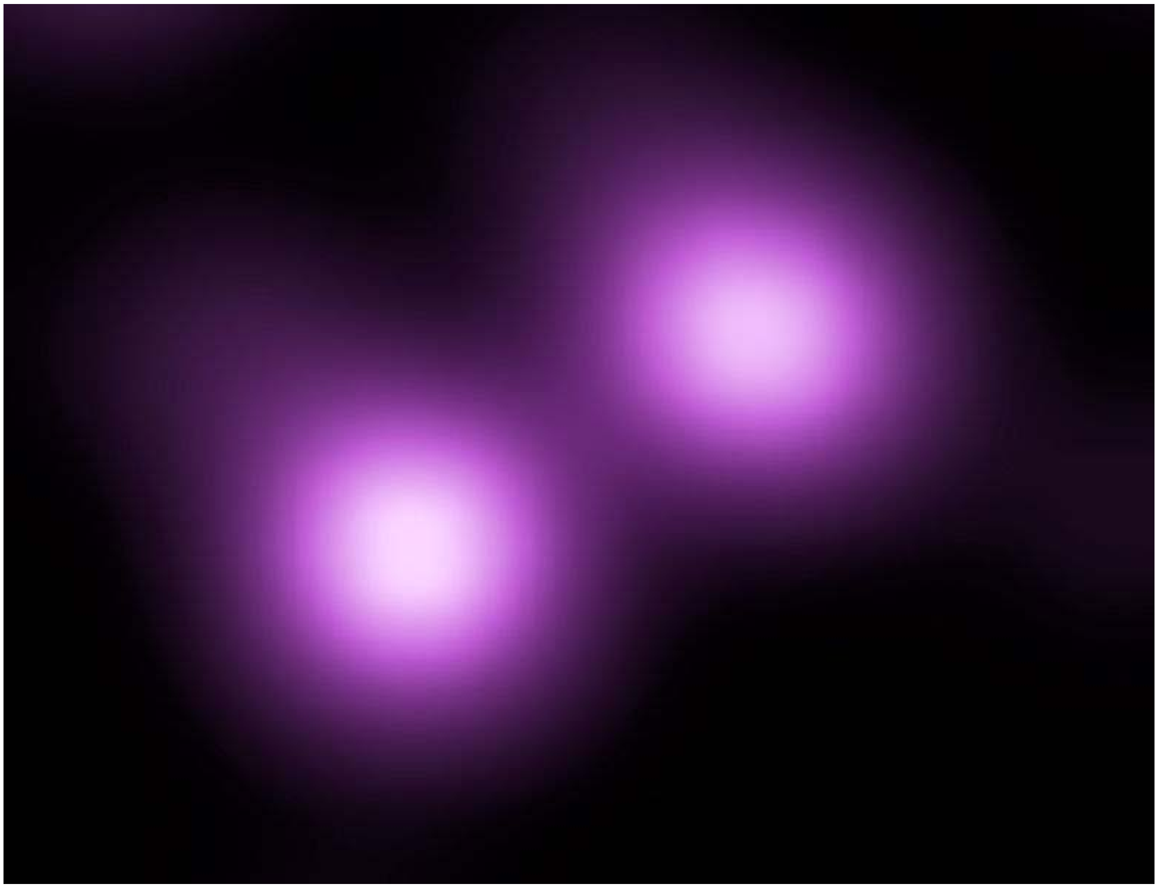
In 1976 the Chandra X-ray Observatory (called AXAF at the time) was proposed to NASA by Riccardo Giacconi and Harvey Tananbaum. Preliminary work began the following year at Marshall Space Flight Center (MSFC) and the Smithsonian Astrophysical Observatory (SAO). In the meantime, in 1978, NASA launched the first imaging X-ray telescope, Einstein (HEAO-2), into orbit. Work continued on the Chandra project through 1980s and 1990s. In 1992, to reduce costs, the spacecraft was redesigned. Four of the twelve planned mirrors were eliminated, as were two of the six scientific instruments. Chandra's planned orbit was changed to an elliptical one, reaching one third of the way to the Moon's at its farthest point. This eliminated the possibility of improvement or repair by the space shuttle but put the observatory above the Earth's radiation belts for most of its orbit.

AXAF was renamed Chandra in 1998 and launched in 1999 by the shuttle *Columbia* (STS-93). At 22753 kg, it was the heaviest payload ever launched by the shuttle, a consequence of the two-stage Inertial Upper Stage booster rocket system needed to transport the spacecraft to its high orbit.

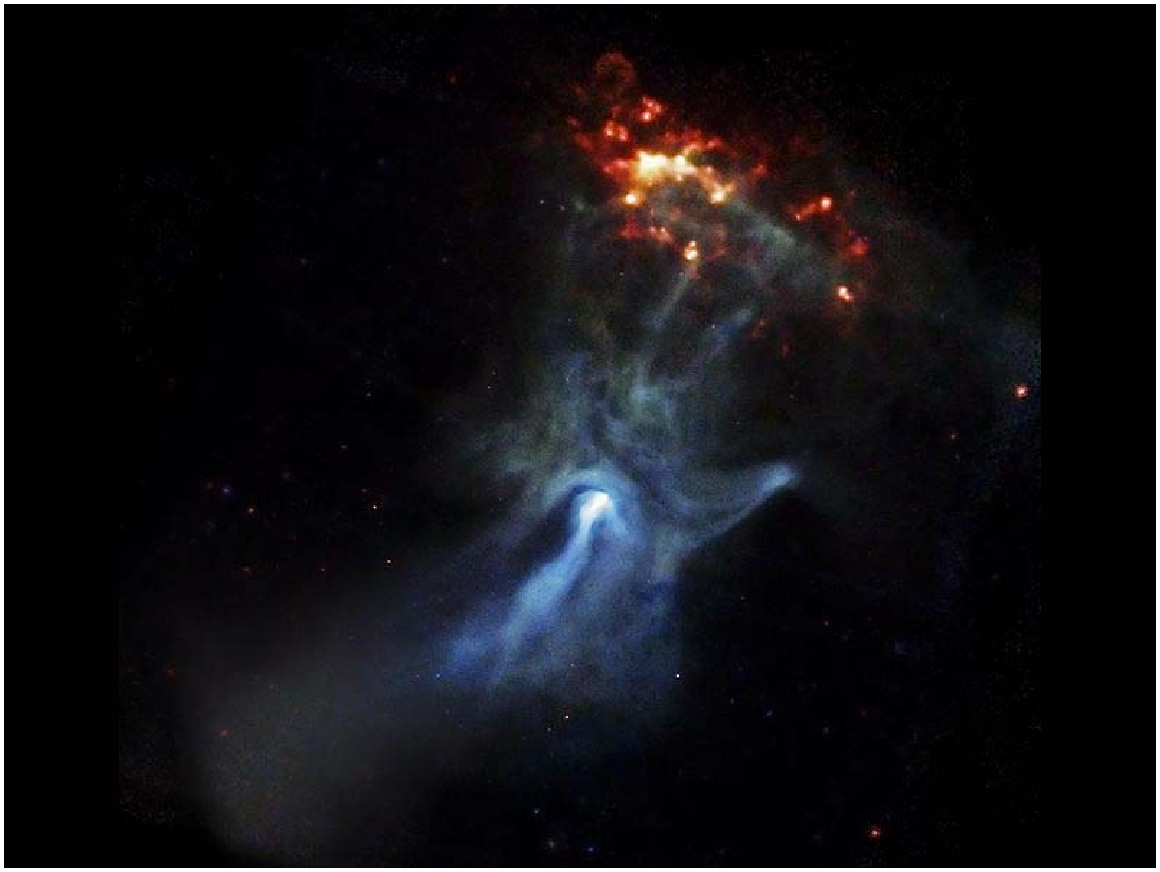
Chandra has been returning data since the month after it launched. It is operated by the SAO at the Chandra X-ray Center in Cambridge, Massachusetts, with assistance from MIT and Northrop Grumman Space Technology. The ACIS CCDs suffered particle damage during early radiation belt passages. To prevent further damage, the instrument is now removed from the telescope's focal plane during passages.

Although Chandra was initially given an expected lifetime of 5 years, on 4 September 2001 NASA extended its lifetime to 10 years "based on the observatory's outstanding results." Physically Chandra could last much longer. A study performed at the Chandra X-ray Center indicated that the observatory could last at least 15 years. On 24 July 2008 the International X-Ray Observatory (IXO), a joint project between ESA, NASA and JAXA, was proposed as the next major X-ray observatory. Its expected launch date is 2020.

Discoveries



SN 2006gy (upper right) and its parent galaxy NGC 1260 (lower left) in false color as observed through the Chandra X-Ray Observatory.



In this image of PSR B1509-58, the lowest energy X-rays that Chandra detects are red, the medium range is green, and the most energetic ones are colored blue.

The data gathered by Chandra have greatly advanced the field of X-ray astronomy.

- The first light image, of supernova remnant Cassiopeia A, gave astronomers their first glimpse of the compact object at the center of the remnant, probably a neutron star or black hole. (Pavlov, *et al.*, 2000)
- In the Crab Nebula, another supernova remnant, Chandra showed a never-before-seen ring around the central pulsar and jets that had only been partially seen by earlier telescopes. (Weisskopf, *et al.*, 2000)
- The first X-ray emission was seen from the supermassive black hole, Sagittarius A*, at the center of the Milky Way. (Baganoff, *et al.*, 2001)
- Chandra found much more cool gas than expected spiralling into the center of the Andromeda Galaxy.
- Pressure fronts were observed in detail for the first time in Abell 2142, where clusters of galaxies are merging.
- The earliest images in X-rays of the shock wave of a supernova were taken of SN 1987A.
- Chandra showed for the first time the shadow of a small galaxy as it is being cannibalized by a larger one, in an image of Perseus A.

- A new type of black hole was discovered in galaxy M82, mid-mass objects purported to be the missing link between stellar-sized black holes and supermassive black holes. (Griffiths, *et al.*, 2000)
- X-ray emission lines were associated for the first time with a gamma-ray burst, Beethoven Burst GRB 991216. (Piro, *et al.*, 2000)
- High school students, using Chandra data, discovered a neutron star in supernova remnant IC 443.
- Observations by Chandra and BeppoSAX suggest that gamma-ray bursts occur in star-forming regions.
- Chandra data suggested that RX J1856.5-3754 and 3C58, previously thought to be pulsars, might be even denser objects: quark stars. These results are still debated.
- Sound waves from violent activity around a supermassive black hole were observed in the Perseus Cluster (2003).
- TWA 5B, a brown dwarf, was seen orbiting a binary system of Sun-like stars.
- Nearly all stars on the main sequence are X-ray emitters. (Schmitt & Liefke, 2004)
- The X-ray shadow of Titan was seen when it transitted the Crab Nebula.
- X-ray emissions from materials falling from a protoplanetary disc into a star. (Kastner, *et al.*, 2004)
- Hubble constant measured to be 76.9 km/s/Mpc using Sunyaev-Zel'dovich effect.
- 2006 Chandra found strong evidence that dark matter exists by observing supercluster collision
- 2006 X-ray emitting loops, rings and filaments discovered around a supermassive black hole within Messier 87 imply the presence of pressure waves, shock waves and sound waves. The evolution of Messier 87 may have been dramatically affected.
- Observations of the Bullet cluster put limits on the cross-section of the self-interaction of dark matter.
- "The Hand of God" photograph of PSR B1509-58.

Technical description

Unlike optical telescopes which possess simple aluminized parabolic surfaces (mirrors), X-ray telescopes generally use a Wolter telescope consisting of nested cylindrical paraboloid and hyperboloid surfaces coated with iridium or gold. X-ray photons would be absorbed by normal mirror surfaces, so mirrors with a low grazing angle are necessary to reflect them. Chandra uses four pairs of nested mirrors, together with their support structure, called the High Resolution Mirror Assembly (HRMA); the mirror substrate is 2 cm-thick glass, with the reflecting surface a 33 nm iridium coating, and the diameters are 65 cm, 87 cm, 99 cm and 123 cm. The thick substrate and particularly careful polishing allowed a very precise optical surface, which is responsible for Chandra's unmatched resolution: between 80% and 95% of the incoming X-ray energy is focused into a one-arcsecond circle. However, the thickness of the substrates limit the proportion of the aperture which is filled, leading to the low collecting area compared to XMM-Newton.

Chandra's highly elliptical orbit allows it to observe continuously for up to 55 hours of its 65 hour orbital period. At its furthest orbital point from earth, Chandra is one of the furthest from earth earth-orbiting satellites. This orbit takes it beyond the geostationary satellites and beyond the outer Van Allen belt.

With an angular resolution of 0.5 arcsecond (2.4 µrad), Chandra possesses a resolution over one thousand times better than that of the first orbiting X-ray telescope.

Instruments

The Science Instrument Module (SIM) holds the two focal plane instruments, the Advanced CCD Imaging Spectrometer (ACIS) and the High Resolution Camera (HRC), moving whichever is called for into position during an observation.

ACIS consists of 10 CCD chips and provides images as well as spectral information of the object observed. It operates in the range of 0.2 - 10 keV. HRC has two micro-channel plate components and images over the range of 0.1 - 10 keV. It also has a time resolution of 16 microseconds. Both of these instruments can be used on their own or in conjunction with one of the observatory's two transmission gratings.

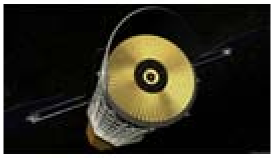
The transmission gratings, which swing into the optical path behind the mirrors, provide Chandra with high resolution spectroscopy. The High Energy Transmission Grating Spectrometer (HETGS) works over 0.4 - 10 keV and has a spectral resolution of 60-1000. The Low Energy Transmission Grating Spectrometer (LETGS) has a range of 0.09 - 3 keV and a resolution of 40-2000.

Chapter- 5

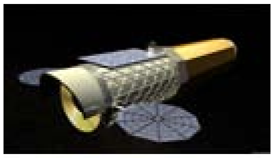
International X-ray Observatory

International X-ray Observatory

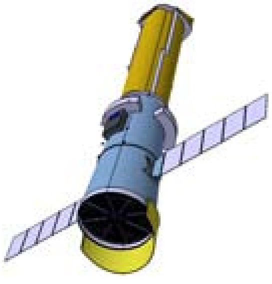
	General information
Organization	NASA European Space Agency Japan Aerospace Exploration Agency
Launch date	2021
Launch vehicle	Ariane V or Atlas V
Wavelength	X-ray
Collecting area	3 square metres (32 sq ft)
Focal length	20 metres (66 ft)



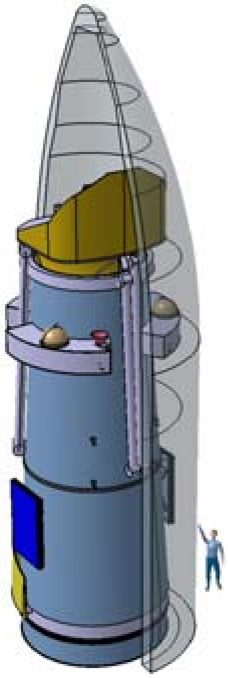
NASA conception of IXO, mirror view, artist's impression



NASA conception of IXO, side view, artist's impression



ESA conception of IXO, schematic diagram of IXO articulated and deployed, artist's impression.



ESA conception of IXO, IXO stowed in an Ariane V fairing, artist's impression.

The **International X-ray Observatory** (**IXO**) is an X-ray telescope to be launched in 2021 as a joint effort by the United States space agency NASA, the European Space Agency (ESA), and the Japan Aerospace Exploration Agency (JAXA). In May 2008, ESA and NASA established a coordination group involving all three agencies, with the intent of exploring a joint mission merging the ongoing XEUS and Constellation-X projects. This proposed the start of a joint study for IXO. IXO still faces funding competition from two other missions, the Europa Jupiter System Mission (EJSM) and the Laser Interferometer Space Antenna (LISA). In 2013 only one of these missions will be chosen.

Science with IXO

X-ray observations are crucial for understanding the structure and evolution of the stars, galaxies, and the Universe as a whole. X-ray images reveal hot spots in the Universe—regions where particles have been energized or raised to very high temperatures by strong magnetic fields, violent explosions, and intense gravitational forces. X-ray sources in the sky are also associated with the different phases of stellar evolution such as the supernova remnants, neutron stars, and black holes.

IXO will explore X-ray Universe and address the following fundamental and timely questions in astrophysics:

- What happens close to a black hole?
- How did supermassive black holes grow?
- How do large scale structures form?
- What is the connection between these processes?

To address these science questions, IXO will trace orbits close to the event horizon of black holes, measure black hole spin for several hundred active galactic nuclei (AGN), use spectroscopy to characterize outflows and the environment of AGN during their peak activity, search for supermassive black holes out to redshift $z = 10$, map bulk motions and turbulence in galaxy clusters, find the missing baryons in the cosmic web using background quasars, and observe the process of cosmic feedback where black holes inject energy on galactic and intergalactic scales.

This will allow astronomers to understand better the history and evolution of matter and energy, visible and dark, as well as their interplay during the formation of the largest structures.

Closer to home, IXO observations will constrain the equation of state in neutron stars, black holes spin demographics, when and how elements were created and dispersed into the intergalactic medium, and much more.

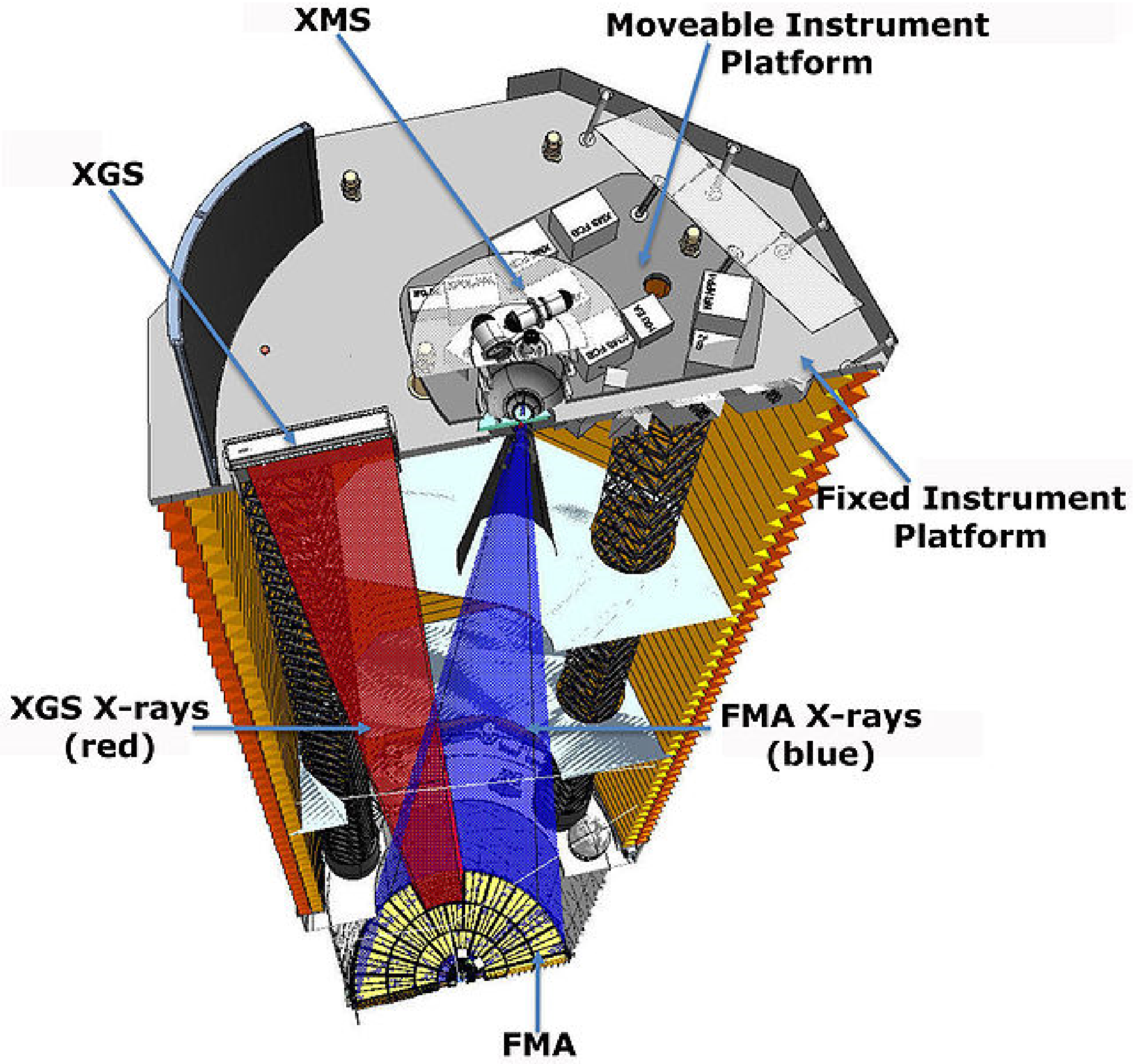
To achieve these science goals, IXO requires extremely large collecting area combined with good angular resolution in order to offer unmatched sensitivities for the study of the high-z Universe and for high-precision spectroscopy of bright X-ray sources.

The large collecting area required because, in astronomy, telescopes gather light and produce images by hunting and counting photons. The number of photons collected puts the limit to our knowledge about the size, energy, or mass of an object detected. More photons collected means better images and better spectra, and therefore offers better possibilities for understanding of cosmic processes.

IXO configuration

The heart of IXO mission is a single large X-ray mirror with up to 3 square meters of collecting area and 5 arcsec angular resolution, which is achieved with an extendable optical bench with a 20 m focal length.

Optics



IXO - cutaway view. X-ray beams reaching detectors, which will provide complementary spectroscopy, imaging, timing, and polarimetry data on cosmic X-ray sources.

A key feature of the IXO mirror design is a single mirror assembly (Flight Mirror Assembly, FMA), which is optimized to minimize mass while maximizing the collecting area, and an extendible optical bench.

Unlike visible light, X-rays cannot be focused at normal incidence, since the X-ray beams would be absorbed in the mirror. Instead, IXO's mirrors, like all prior X-ray telescopes, will use grazing incidences, scattering at a very shallow angle. As a result, X-ray telescopes consist of nested cylindrical shells, with their inner surface being the reflecting surface. However, as the goal is to collect as many photons as possible, IXO will have a bigger than 3m diameter mirror.

As the grazing angle is a function inversely proportional to photon energy, the higher-energy X-rays require smaller (less than 2 degrees) grazing angles to be focused. This implies longer focal lengths as the photon energy increases, thus making X-ray telescopes difficult to build if focusing of photons with energies higher than a few keV is desired. For that reason IXO features an *extendible optical bench* that offers a focal length of 20 m. A focal length of 20 meters was selected for IXO as a reasonable balance between scientific needs for advanced photon collecting capability at the higher energy ranges and engineering constraints. Since no payload fairing is large enough to fit a 20-meter long observatory, thus IXO has a deployable metering structure between the spacecraft bus and the instrument module.

Instrumentation

IXO scientific goals require gathering many pieces of information using different techniques such as spectroscopy, timing, imaging, and polarimetry. Therefore, IXO will carry a range of detectors, which will provide complementary spectroscopy, imaging, timing, and polarimetry data on cosmic X-ray sources to help disentangle the physical processes occurring in them.

Two high-resolution spectrometers, a microcalorimeter (XMS or cryogenic imaging spectrograph (CIS)) and a set of dispersive gratings (XGS) will provide high-quality spectra over the 0.1 – 10 keV bandpass where most astrophysically abundant ions have X-ray lines. The detailed spectroscopy from these instruments will enable high-energy astronomers to learn about the temperature, composition, and velocity of plasmas in the Universe. Moreover, the study of specific X-ray spectral features probes the conditions of matter in extreme gravity field, such as around supermassive black holes. Flux variability adds a further dimension by linking the emission to the size of the emitting region and its evolution over time; the high timing resolution spectrometer (HTRS) on IXO will allow these types of studies in a broad energy range and with high sensitivity.

To extend our view of the high-energy Universe to the hard X-rays and find the most obscured black holes, the wide field imaging & hard X-ray imaging detectors (WFI/HXI) together will image the sky up to 18 arcmin field of view (FOV) with a moderate resolution (<150 eV up to 6 keV and <1 keV (FWHM) at 40 keV.

IXO's imaging X-ray polarimeter will be a powerful tool to explore sources such as neutron stars and black holes, measuring their properties and how they impact their surroundings.

The detectors will be located on two instrument platforms—the Moveable Instrument Platform (MIP) and the Fixed Instrument Platform (FIP). The Moveable Instrument Platform is needed because an X-ray telescopes cannot be folded as it can be done with visible-spectrum telescopes. Therefore, IXO will use the MIP that holds the following detectors—a wide field imaging & hard X-ray imaging detector, a high-spectral-resolution imaging spectrometer, a high timing resolution spectrometer, and a polarimeter — and rotates them into the focus in turn.

The X-ray Grating Spectrometer will be located on the Fixed Instrument Platform. This is a wavelength-dispersive spectrometer that will provide high spectral resolution in the soft X-ray band. It can be used to determine the properties of the warm-hot-intergalactic medium, outflows from active galactic nuclei, and plasma emissions from stellar coronae.

A fraction of the beam from the mirror will be dispersed to a charge-coupled device (CCD) camera, which will operate simultaneously with the observing MIP instrument and collect instrumental background data, which can occur when an instrument is not in the focal position.

To avoid interfering the very faint astronomical signals with radiation from the telescope, the telescope itself and all its instruments must be kept cold. Therefore, the IXO Instrument Platform features a large shield that blocks the light from the Sun, Earth, and Moon, which otherwise would heat up the telescope, and interfere with the observations.

IXO optics and instrumentation will provide up to 100-fold increase in effective area for high resolution spectroscopy, deep spectral, and microsecond spectroscopic timing with high count rate capability.

The improvement of IXO relative to current X-ray missions is equivalent to a transition from the 200 inch Palomar telescope to a 22 m telescope while at the same time shifting from spectral band imaging to an integral field spectrograph.

Launch

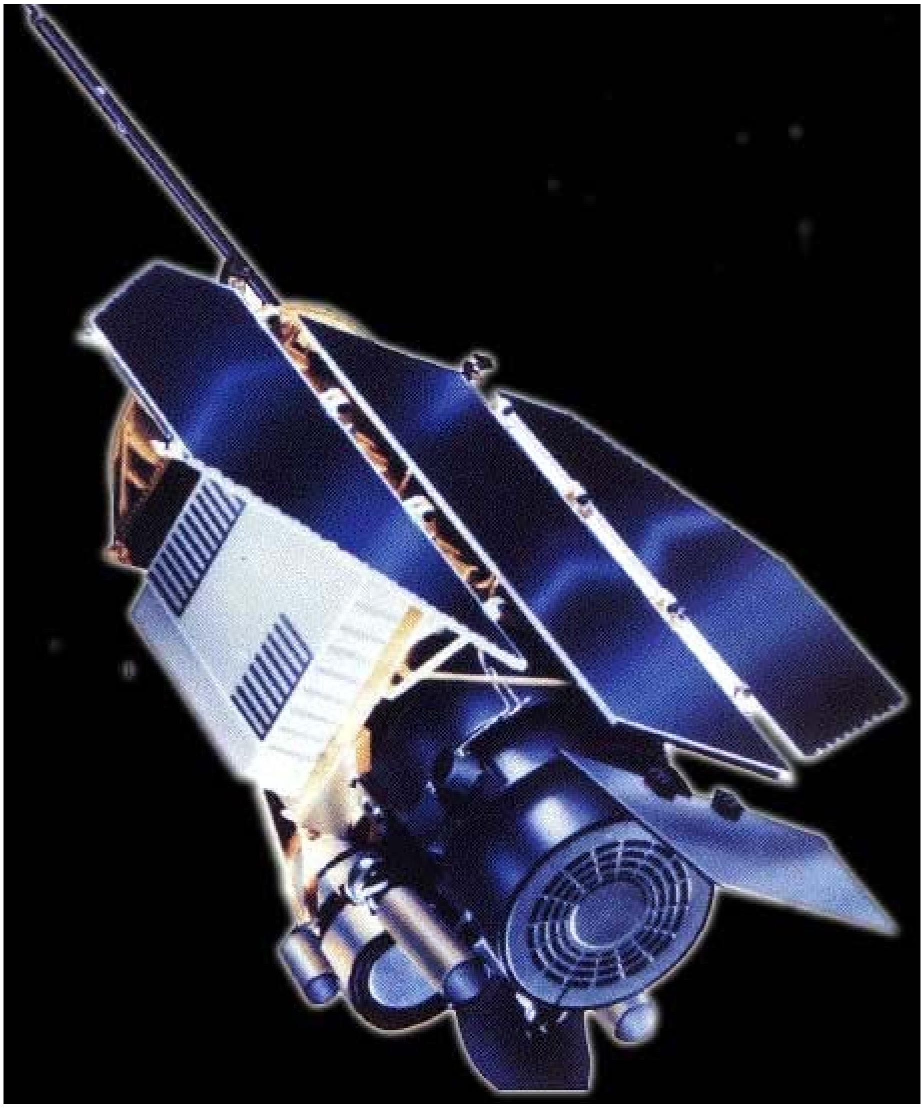
The planned launch date for IXO is 2021, going into an L2 orbit. Studies to determine the launch vehicle, either the Ariane V or Atlas V, are currently underway.

Science operations

IXO will be designed to operate for a minimum of 5 years, with a goal of 10 years, so IXO science operations are anticipated to last from 2021 to 2030.

Chapter- 6

ROSAT



ROSAT

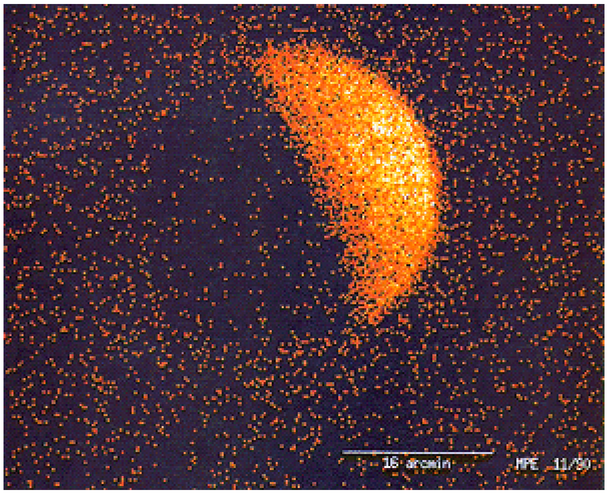
ROSAT (short for **Rö**ntgen**sat**ellit) was a German X-ray satellite telescope. It was named in honour of Wilhelm Röntgen. It was launched on June 1, 1990, with a Delta II rocket from Cape Canaveral, and operated until February 12, 1999.

Overview

The Roentgensatellit (ROSAT) was a joint German, US and British X-ray astrophysics project. ROSAT carried a German-built imaging X-ray Telescope (XRT) with three focal plane instruments: two German Position Sensitive Proportional Counters (PSPC) and the US-supplied High Resolution Imager (HRI). The X-ray mirror assembly was a grazing incidence four-fold nested Wolter I telescope with an 84-cm diameter aperture and 240-cm focal length. The angular resolution was <5 arcsec at half energy width. The XRT assembly was sensitive to X-rays between 0.1 to 2 keV. In addition, a British-supplied extreme ultraviolet (XUV) telescope, the Wide Field Camera (WFC), was coaligned with the XRT and covers the wave band between and 6 angstroms (0.042 to 0.21 keV). ROSAT's unique strengths were high spatial resolution, low-background, soft X-ray imaging for the study of the structure of low surface brightness features, and for low-resolution spectroscopy. The ROSAT spacecraft was a three-axis stablized satellite which can be used for pointed observations, for slewing between targets, and for performing scanning observations on great circles perpendicular to the plane of the ecliptic. ROSAT was capable of fast slews (180 deg. in ~15 min.) which makes it possible to observe two targets on opposite hemispheres during each orbit. The pointing accuracy was 1 arcminute with stability <5 arcsec per sec and jitter radius of ~10 arcsec. Two CCD star sensors were used for optical position sensing of guide stars and attitude determination of the spacecraft. The post facto attitude determination accuracy was 6 arcsec. The ROSAT mission was divided into two phases: (1) After a two-month on-orbit calibration and verification period, an all-sky survey was performed for six months using the PSPC in the focus of XRT, and in two XUV bands using the WFC. The survey was carried out in the scan mode. (2) The second phase consists of the remainder of the mission and was devoted to pointed observations of selected astrophysical sources. In ROSAT's pointed phase, observing time was allocated to Guest Investigators from all three participating countries through peer review of submitted proposals. ROSAT had a design life of 18 months, but was expected to operate beyond its nominal lifetime.

— NASA

Highlights



Earth's Moon on June 29, 1990 by ROSAT

- X-ray all-sky survey catalog, more than 150000 objects
- XUV all-sky survey catalog (479 objects)
- Source catalogs from the pointed phase (PSPC and HRI) containing ~ 100000 serendipitous sources
- Detailed morphology of supernova remnants and clusters of galaxies.
- Detection of shadowing of diffuse X-ray emission by molecular clouds.
- Detection of pulsations from Geminga.
- Detection of isolated neutron stars.
- Discovery of X-ray emission from comets.
- Observation of X-ray emission from the collision of Comet Shoemaker-Levy with Jupiter.

Catalogues

- 1RXS - First ROSAT X-ray Survey

Launch

ROSAT was originally planned to be launched on the Space shuttle but the Challenger disaster caused it to be moved to the Delta platform.

Failures and end of life

Originally designed for a 5 year mission, ROSAT continued in its extended mission for a further 4 years before equipment failure forced an end to the mission. For some months after this, ROSAT completed its very last observations before being finally switched off on 12 February 1999.

There is some recent controversy over the precise causes of ROSAT's demise.

On 25 April 1998, failure of the primary star tracker on the X-ray Telescope led to pointing errors that in turn had caused solar overheating. A contingency plan and the necessary software had already been developed to utilise an alternative star tracker attached to the Wide Field Camera.

ROSAT was soon operational again, but with some restrictions to the effectiveness of its tracking and thus its control. It was severely damaged on September 20, 1998 when a reaction wheel in the spacecraft's Attitude Measuring and Control System (AMCS) achieved its maximum rotational speed, losing control of a slew, damaging the High Resolution Imager by exposure to the sun. This failure was initially attributed to the difficulties of controlling the satellite under these difficult circumstances outside its initial design parameters. A reaction wheel operates by changing its rotational velocity, conservation of angular momentum then causing the more massive satellite to rotate in opposition. Their maximum speed is limited by design, which in turn means they are limited in the velocity they can impart to a satellite. "Reaching maximum speed" thus means merely that it cannot impart any more velocity change, not that it's approaching mechanical damage to itself.

As of April 2009, the satellite continues to orbit approximately 390 km above the Earth.

Allegations of cyber-attacks causing the failure

Ten years later in 2008, NASA investigators were reported to have found that the ROSAT failure was linked to a cyber-intrusion at Goddard Space Flight Center. This was also reported through Bruce Schneier's blog, a highly-regarded commentary on IT security issues.

The root of this allegation is a 1999 advisory report by Thomas Talleur, senior investigator for cyber-security at NASA. This advisory is reported to describe a series of attacks from Russia that reached computers in the X-ray Astrophysics Section (i.e. ROSAT's) at Goddard, and took control of computers used for the control of satellies, not just a passive "snooping" attack. The advisory stated:

"Hostile activities compromised [NASA] computer systems that directly and indirectly deal with the design, testing, and transferring of satellite package command-and-control codes."

The advisory is further reported as claiming that the ROSAT incident was "coincident with the intrusion" and that, "Operational characteristics and commanding of the ROSAT were sufficiently similar to other space assets to provide intruders with valuable information about how such platforms are commanded,". Without public access to the advisory, it is obviously impossible to comment in detail. However it does seem to describe a real intrusion, there is a plausible "no attack" explanation for ROSAT's failure, and the report is claimed to link the two incidents as no more than "coincident". IT security remains a significant issue for NASA, other systems including the Earth Observing System having also been attacked.

Chapter- 7

GALEX

Galaxy Evolution Explorer (GALEX)

Artist's impression of GALEX

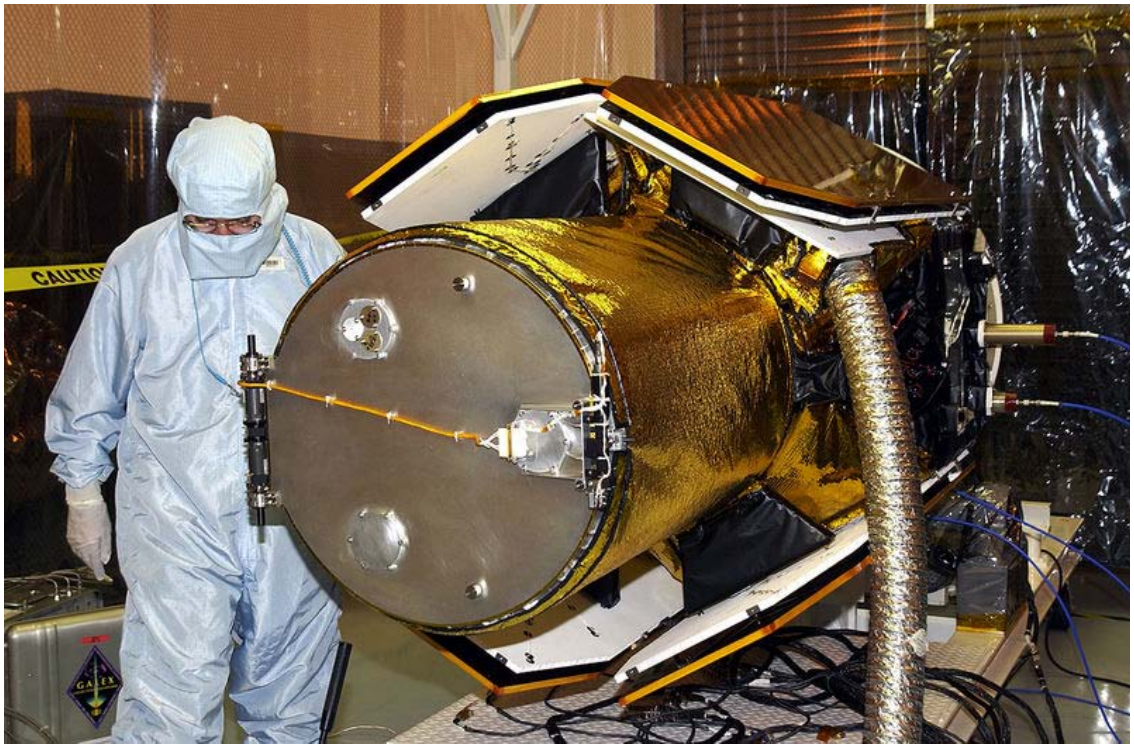
General information

NSSDC ID	2003-017A
Organization	NASA / JPL / Caltech
Major contractors	Orbital Sciences Corporation
Launch date	2003-04-28 11:59:54 UTC

Launched from	~ 60 km offshore from Cape Canaveral Air Force Station
Launch vehicle	L-1011 Stargazer / Pegasus XL
Mass	280 kilograms (620 lb)
Type of orbit	Near-circular
Orbit height	697 kilometres (433 mi)
Location	Low Earth orbit
Telescope style	Richey-Chrétien
Wavelength	135 to 280 nm (Ultraviolet)
Diameter	0.5 m
Focal length	3 m

The **Galaxy Evolution Explorer (GALEX)** is an orbiting ultraviolet space telescope launched on April 28, 2003. A Pegasus rocket placed the craft into a nearly circular orbit at an altitude of 697 kilometres (433 mi) and an inclination to the Earth's equator of 29 degrees.

The first observation was dedicated to the crew of the Space Shuttle Columbia and images the sky in the constellation Hercules, taken on May 21, 2003. This region was selected because it had been directly overhead the shuttle at the time of its last contact with the NASA Mission Control Center.



GALEX at the pre-launch tests

GALEX being mated to a Pegasus XL Rocket

GALEX's Pegasus XL being attached to the L-1011 Stargazer

The Lockheed L-1011 Stargazer take-off with GALEX attached under-belly

Science mission

During its nominal 29-month mission it makes observations at ultraviolet wavelengths to measure the history of star formation in the universe 80 percent of the way back to the Big Bang. Since scientists believe the Universe to be about 13.7 billion years old, the mission will study galaxies and stars across about 10 billion years of cosmic history.

The spacecraft's mission is to observe hundreds of thousands of galaxies, with the goal of determining the distance of each galaxy is from Earth and the rate of star formation in each galaxy. Near- and far-UV emissions as measured by GALEX can indicate the presence of young stars, but may also originate from old stellar populations (e.g. sdB stars).

Partnering with the NASA Jet Propulsion Laboratory (JPL) on the mission are the California Institute of Technology, Orbital Sciences Corporation, University of California, Berkeley, Yonsei University, Johns Hopkins University, Columbia University, and Laboratoire d'Astrophysique de Marseille, France.

Chapter- 8

TAUVEX

The **Tel Aviv University Ultraviolet Explorer**, or **TAUVEX**, is a space telescope array designed and constructed in Israel for Tel Aviv University by El-Op , Electro-Optical Industries, Ltd. (a division of Elbit systems), for the exploration of the ultraviolet (UV) sky. TAUVEX was selected in 1988 by the Israel Space Agency (ISA) as its first priority scientific payload. Although originally slated to fly on a national Israeli satellite of the Ofeq series, TAUVEX was shifted in 1991 to fly as part of the Spectrum Roentgen-Gamma (SRG) international observatory, a collaboration of a large number of countries with the Soviet Union (Space Research Institute) leading.

Due to repeated delays of the SRG project, caused by the economic situation in the post-Soviet Russia, ISA decided to shift TAUVEX to a different satellite. In early-2004 ISA signed an agreement with the Indian Space Research Organization (ISRO) to launch TAUVEX on board the Indian technology demonstrator satellite GSAT-4. The launch vehicle slated to be used is the GSLV with a new, cryogenic, upper stage. TAUVEX is a scientific collaboration between Tel Aviv University and the Indian Institute of Astrophysics in Bangalore. Its Principal Investigators are Noah Brosch at Tel Aviv University and Jayant Murthy at the Indian Institute of Astrophysics. Originally, TAUVEX was scheduled to be launched in 2008. but various delays caused the integration with GSAT-4 to take place only in November 2009 for a launch the following year. ISRO decided in January 2010 to remove TAUVEX from the satellite since the Indian-built cryogenic upper stage for GSLV was deemed under-powered to bring GSAT-4 to a geosynchronous orbit. GSAT-4 was subsequently lost in the 15 April 2010 launch failure of GSLV.

Instrumentation

TAUVEX consists of three bore-sighted 20 cm diameter telescopes on a single bezel, called telescopes A, B, and C. Each telescope images the same sky area of 0.9 degree, with an angular resolution of 7-11 arcseconds. The imaging is onto position-sensitive detectors (CsTe cathodes on calcium fluoride windows) equipped with multi-channel plate electron intensifiers. The detectors oversample the point-spread-function by a factor of approximately three. The output is detected by position-sensitive anodes (wedge-and-strip) and is digitized to 12 bits. The full image of each telescope has about 300 resolution elements across its diameter.

The type of cathode (CsTe) assures sensitivity from longward of Lyman α to the atmospheric limit with a peak quantum efficiency of approximately 10%. The operating spectral range is separated in a number of segments selectable with filters. Each telescope [T] is equipped with a four-position filter wheel. Each wheel contains one blocked position (shutter) and three band-selection filters [Fn]. The filter complement, and its distribution among the three telescopes, is as follows:

T	F1	F2	F3	F4
A	BBF	SF1	SF2	Shutter
B	Shutter	SF1	NBF3	SF3
C	BBF	Shutter	SF2	SF3

The approximate characteristics of each filter type are summarized below:

Filter	Wavelength	Width	Normalized transmission
BBF	2300 Å (230 nm)	1000 Å (100 nm)	80%
SF1	1750 Å (175 nm)	400 Å (40 nm)	20%
SF2	2200 Å (200 nm)	400 Å (40 nm)	45%
SF3	2600 Å (260 nm)	500 Å (50 nm)	40%
NBF3	2200 Å (220 nm)	200 Å (20 nm)	30%

TAUVEX was mounted to the GSAT-4 spacecraft on a plate that could rotate around its axis (the MDP), enabling to point the telescopes' line-of-sight to any desired declination. Being on a geostationary satellite, the observation would therefore have been of a scanning type. A 'ribbon' of a constant declination, 0.9 degree wide, would have been scanned as time advanced, completing an entire 360 degree circuit during one sidereal day. In this mode of operation, the dwell time of a source within the detector field of view is a function of the pointing declination and of the exact location in the FOV relative to the detector diameter. The closer a source is to one of the celestial poles, the longer it resides in the TAUVEX field of view during a single scan. The longest theoretically-possible exposure is for sources at |δ|>89°30'; these could be observed all day.

The interface with GSAT-4 ensured that each photon event hitting the detectors would have been transmitted to the ground in real time and processed in a near-real-time pipeline. In-between the photon events a time tag is added every 128 ms. The time between the adjacent time tags is sufficiently short so that the orbital motion of the nadir-pointing platform is much smaller than the TAUVEX virtual pixel.

Given that TAUVEX on GSAT-4 was planned to operate from a geo-synchronous platform that is, essentially, a telecommunications satellite, it is clear that up and downlink telemetry are much less problematic that with other astronomical satellites. In fact, TAUVEX was allowed a dedicated 1 Mbit/s downlink to the ISRO Master Control Facility (MCF) at Hassan, near Bangalore. Command sequences were planned to be uplinked after being generated by IIA and ISRO and the downlink to be analyzed on-line to monitor the payload state of health.

In most situations, TAUVEX would have been able to download all the detected photon events. However, in case of strong straylight or of many bright sources in the field of view, the collected event rate could overload the capacity of the telemetry link. In this case, TAUVEX would have stored the photon events in a solid state memory module (4 GB), from which the events are transmitted at the nominal 1 Mbit/s rate.

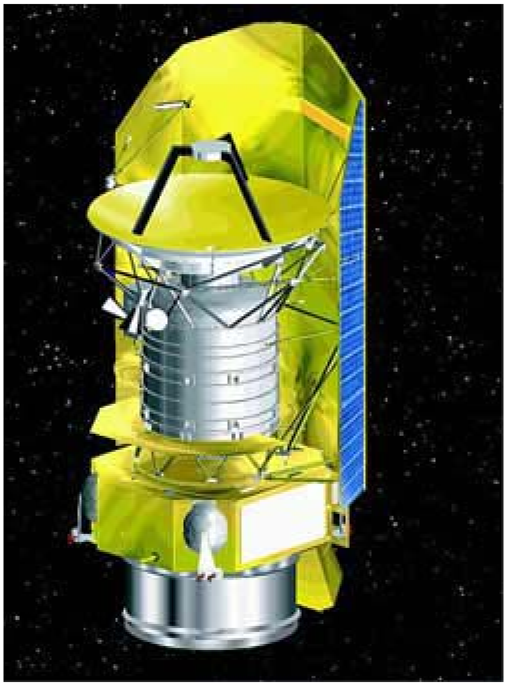
Science with TAUVEX

The science of TAUVEX is based on its unique characteristics: three bore-sighted and independent telescopes able to operate independently, with different filters but measuring the same sources, and reasonably fine time resolution as every detected photon is time-tagged. A unique possibility allows the study of the interstellar dust band at 217.4 nm; the two TAUVEX filters SF2 and NBF3 are centered on this wavelength but have different widths. As the filters are located on different telescopes, it is possible to measure the same sky region with both filters simultaneously, deriving the equivalent width of the band for every star in the field of view. The use of TAUVEX as a scientific instrument is the result of calibration on the ground .This calibration was very difficult and produced unreliable results. The Principal Investigators planned to repeat and improve the calibration in space, following the launch.

Chapter- 9

Herschel Space Observatory

Herschel Space Observatory



General information

NSSDC ID	2009-026A
Organization	European Space Agency (ESA) NASA
Major contractors	Thales Alenia Space
Launch date	2009:05:14, 13:12:02 UTC
Launched from	Guiana Space Centre French Guiana

Launch vehicle	Ariane 5 ECA
Mission length	planned: 3 years elapsed: 1 year, 8 months, and 21 days
Mass	3,300 kg (7,300 lb)
Type of orbit	Lissajous orbit
Orbit height	1,500,000 km (930,000 mi)
Orbit period	1 year
Orbit velocity	7,500 m/s (27,000 km/h)
Location	Lagrangian point L_2
Telescope style	Ritchey-Chrétien
Wavelength	60-670 µm (far-infrared)
Diameter	3,500 mm (140 in), f/0.5 (Primary Mirror)
Collecting area	9.6 m^2 (103 sq ft)
Focal length	28.5 m (94 ft), f/8.7
	Instruments
HIFI	Heterodyne Instrument for the Far Infrared
PACS	Photodetector Array Camera and Spectrometer
SPIRE	Spectral and Photometric Imaging Receiver

The **Herschel Space Observatory** is a European Space Agency space observatory sensitive to the far infrared and submillimetre wavebands. It is the largest space telescope ever launched carrying a single mirror of 3.5 meter in diameter.

The observatory was carried into orbit in May 2009, reaching the second Lagrangian point (L2) of the Earth-Sun system, 1,500,000 kilometres (930,000 mi) from the Earth, about two months later. Herschel is named after Sir William Herschel, the discoverer of the infrared spectrum and planet Uranus, and his sister and collaborator Caroline.

The Herschel Observatory is capable of seeing the coldest and dustiest objects in space; for example, cool cocoons where stars form and dusty galaxies just starting to bulk up with new stars. The observatory will sift through star-forming clouds—the "slow cookers" of star ingredients—to trace the path by which potentially life-forming molecules, such as water, form. The United States through NASA is participating in the ESA built and operated observatory. It is the fourth 'cornerstone' mission in the ESA science program, along with Rosetta, Planck, and the Gaia mission.

Science

Herschel will specialise in collecting light from objects in our Solar System as well as the Milky Way and even extragalactic objects billions of light-years away, such as newborn galaxies, and is charged with four primary areas of investigation:

- Galaxy formation in the early universe and the evolution of galaxies;
- Star formation and its interaction with the interstellar medium;
- Chemical composition of atmospheres and surfaces of Solar System bodies, including planets, comets and moons;
- Molecular chemistry across the universe.

Instrumentation

The mission, formerly titled the **Far Infrared and Sub-millimetre Telescope** (**FIRST**), involves the first space observatory to cover the full far infrared and submillimetre waveband. At 3.5 meters wide, its telescope incorporates the largest mirror (made not from glass but from sintered silicon carbide) ever deployed in space. The light is focused onto three instruments with detectors kept at temperatures below 2 K (−271 °C). The instruments are cooled with liquid helium, boiling away in a near vacuum at a temperature of approximately 1.4 K (−272 °C). The 2,000-litre supply of helium on board the spacecraft will limit its operational lifetime, nonetheless it is expected to be operational for at least 3 years.

Herschel carries three detectors:

PACS (Photodetecting Array Camera and Spectrometer)

> An imaging camera and low-resolution spectrometer covering wavelengths from 55 to 210 micrometres. The spectrometer has a spectral resolution between R=1000 and R=5000 and is able to detect signals as weak as −63 dB. It operates as an integral field spectrograph, combining spatial and spectral resolution. The imaging camera can image simultaneously in two bands (either 60–85/85–130 micrometres and 130–210 micrometres) with a detection limit of a few millijanskys.

Herschel in a clean room

SPIRE (Spectral and Photometric Imaging Receiver)

An imaging camera and low-resolution spectrometer covering 194 to 672 micrometre wavelength. The spectrometer has a resolution between R=40 and R=1000 at a wavelength of 250 micrometres and is able to image point sources with brightnesses around 100 millijanskys (mJy) and extended sources with brightnesses of around 500 mJy. The imaging camera has three bands, centered at 250, 350 and 500 micrometres, each with 139, 88 and 43 pixels respectively. It should be able to detect point sources with brightness above 2 mJy and between 4 and 9 mJy for extended sources. A prototype of the SPIRE imaging camera flew on the BLAST high-altitude balloon. NASA's Jet Propulsion Laboratory in

Pasadena, Calif., developed and built the "spider web" bolometers for this instrument, which is 40 times more sensitive than previous versions.

HIFI (Heterodyne Instrument for the Far Infrared)

A heterodyne detector which is able to electronically separate radiation of different wavelengths, giving a spectral resolution as high as $R=10^7$. The spectrometer can be operated within two wavelength bands, from 157 to 212 micrometres and from 240 to 625 micrometres. NASA developed and built the mixers, local oscillator chains and power amplifiers for this instrument.

Service module

A common service module (SVM) was designed and built by Thales Alenia Space in its Turin plant, for the Herschel and Planck missions combined into one single program.

Structurally, the Herschel and Planck SVM's are very similar. Both SVM's are of octagonal shape and for both, each panel is dedicated to accommodate a designated set of warm units, while taking into account the dissipation requirements of the different warm units, of the instruments as well as the spacecraft.

Furthermore, on both spacecraft a common design for the avionics, the attitude control and measurement system (ACMS) and the command and data management system (CDMS), and power subsystem and the tracking, telemetry and command subsystem (TT&C) has been achieved.

All spacecraft units on the SVM are redundant.

Power subsystem

On each spacecraft, the power subsystem consists of the solar array, employing triple-junction solar cells, a battery and the power control unit (PCU). It is designed to interface with the 30 sections of each solar array, provide a regulated 28 V bus, distribute this power via protected outputs and to handle the battery charging and discharging.

For Herschel, the solar array is fixed on the bottom part of the baffle designed to protect the cryostat from the sun. The three-axis attitude control system maintains this baffle in direction of the sun. The top part of this baffle is covered with optical solar reflector (OSR) mirrors reflecting 98% of the sun energy, avoiding heating of the cryostat.

Attitude and orbit control

This function is performed by the attitude control computer (ACC) which is the platform for the ACMS. It is designed to fulfil the pointing and slewing requirements of the Herschel and Planck payload.

The Herschel spacecraft is three-axis stabilized, the absolute pointing error needs to be less than 3.7 arc sec.

The main sensor of the line of sight in both spacecraft is the star tracker.

Launch and orbit

The spacecraft, built in the Cannes Mandelieu Space Center, under Thales Alenia Space Contractorship, was successfully launched from the Guiana Space Centre in French Guiana at 13:12:02 UTC on 14 May 2009, aboard an Ariane 5 rocket, along with the Planck spacecraft, and placed on a very elliptical orbit (perigee: 270.0 km (intended 270.0±4.5), apogee: 1,197,080 km (intended 1,193,622±151,800), inclination 5.99 deg (intended 6.00±0.06)), on its way towards the second Lagrangian point.

On June 14, 2009, ESA successfully sent the command for the cryocover to open which will allow the PACS system to see the sky and transmit images in a few weeks. The lid had to remain closed until the telescope was well into space to prevent contamination. Herschel is reported to have completed 90% of the distance to its orbit 1.5 million km away from Earth.

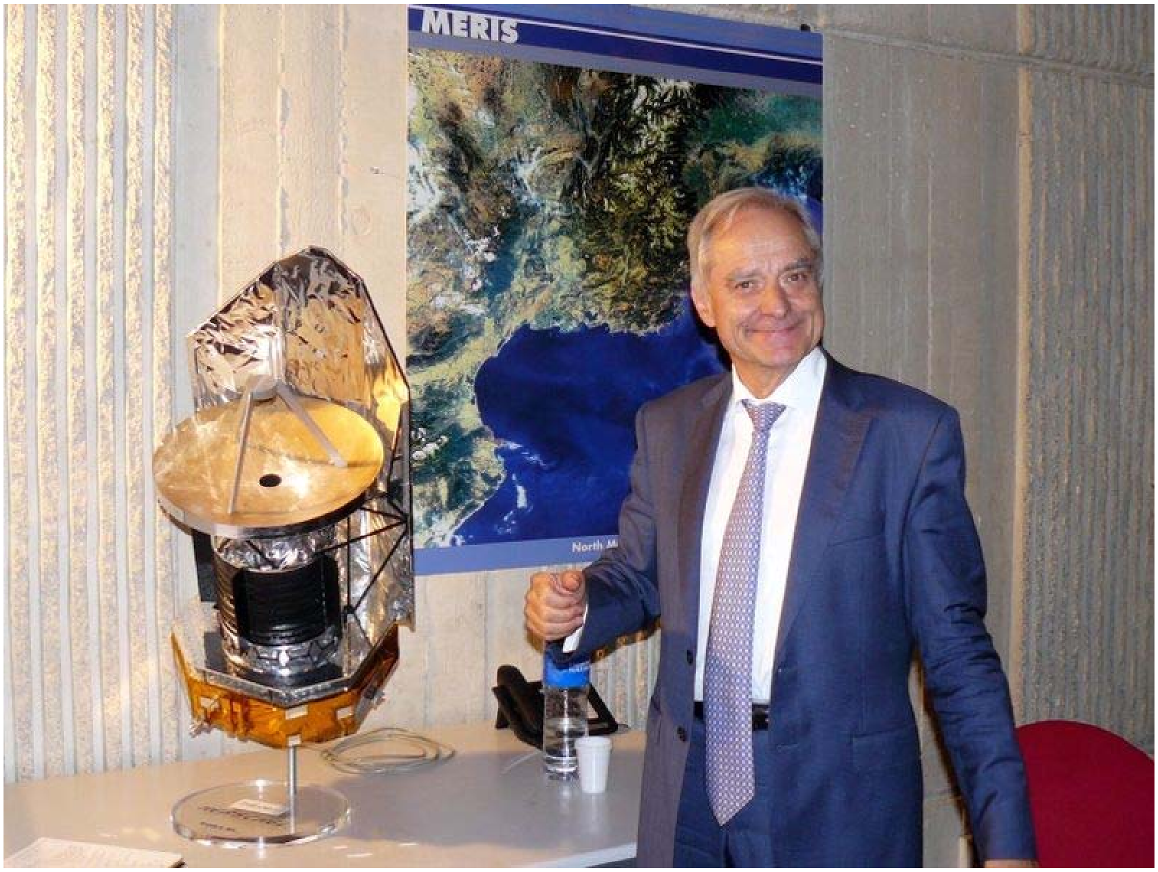
Five days later the first set of test photos, depicting M51 Group, was published by ESA.

In mid-July 2009, approximately sixty days after launch, it entered a Lissajous orbit of 800,000 km average radius around the second Lagrangian point (L2) of the Earth-Sun system, 1.5 million kilometres from the Earth.

Operational mission

On 21 July 2009, Herschel commissioning was declared successful, allowing the start of the operational phase. A formal handover of the overall responsibility of Herschel was declared from the programme manager Thomas Passvogel to the mission manager Johannes Riedinger.

Discoveries



André Brahic, astronomer, one of the fathers of **Herschel** and Planck programmes, during a conference he made in the Cannes Mandelieu Space Center

Herschel was instrumental in the discovery of an unknown and unexpected step in the star forming process. The initial confirmation and later verification via help from ground based telescopes of a vast hole of empty space, previously believed to be a dark nebula, in the area NGC 1999 shed new light in the way newly forming star regions discard the material which surrounds it.

On July 16, 2010, a special issue of *Astronomy and Astrophysics* was published with 152 papers on initial results from the observatory.

Chapter- 10

Spitzer Space Telescope

Spitzer Space Telescope

The Spitzer Space Telescope prior to launch

General information

NSSDC ID	2003-038A
Organization	NASA / JPL / Caltech
Major contractors	Lockheed Martin Ball Aerospace
Launch date	25 August 2003

Launched from	Cape Canaveral, Florida
Launch vehicle	Delta II 7920H ELV
Mission length	2.5 to 5+ years (7 years, 5 months, and 10 days elapsed)
Mass	950 kg (2,100 lb)
Type of orbit	Heliocentric
Orbit period	1 year
Location	Orbiting the Sun
Telescope style	Ritchey-Chrétien
Wavelength	3 to 180 micrometers
Diameter	0.85 m (2 ft 9 in)
Focal length	10.2 m
	Instruments
IRAC	infrared camera
IRS	infrared spectrometer
MIPS	far infrared detector arrays

The **Spitzer Space Telescope (SST)**, formerly the **Space Infrared Telescope Facility (SIRTF)** is an infrared space observatory launched in 2003. It is the fourth and final of NASA's Great Observatories.

The planned mission period was to be 2.5 years with a pre-launch expectation that the mission could extend to five or slightly more years until the onboard liquid helium supply was exhausted. This occurred on 15 May 2009. Without liquid helium to cool the telescope to the very cold temperatures needed to operate, most instruments are no longer usable. However, the two shortest wavelength modules of the IRAC camera are still operable with the same sensitivity as before the cryogen was exhausted, and will continue to be used in the Spitzer Warm Mission.

In keeping with NASA tradition, the telescope was renamed after successful demonstration of operation, on December 18, 2003. Unlike most telescopes which are named after famous deceased astronomers by a board of scientists, the name for SIRTF was obtained from a contest open to the general public.

The contest led to the telescope being named in honor of Lyman Spitzer, one of the 20th century's great scientists. Though he was not the first to propose the idea of the space telescope (Hermann Oberth being the first, in *Wege zur Raumschiffahrt,* 1929, and also in *Die Rakete zu den Planetenräumen,* 1923), Spitzer wrote a 1946 report for RAND describing the advantages of an extraterrestrial observatory and how it could be realized with available (or upcoming) technology. He has been cited for his pioneering contributions to rocketry and astronomy, as well as *"his vision and leadership in articulating the advantages and benefits to be realized from the Space Telescope Program."*

The US$800 million Spitzer was launched from Cape Canaveral Air Force Station, on a Delta II 7920H ELV rocket, Monday, 25 August 2003 at 13:35:39 UTC-5 (EDT).

It follows a rather unusual orbit, heliocentric instead of geocentric, trailing and drifting away from Earth's orbit at approximately 0.1 astronomical unit per year (a so-called "earth-trailing" orbit). The primary mirror is 85 centimetres (33 in) in diameter, *f*/12 and made of beryllium and was cooled to 5.5 K (−449.77 °F). The satellite contains three instruments that allowed it to perform imaging and photometry from 3 to 180 micrometers, spectroscopy from 5 to 40 micrometers, and spectrophotometry from 5 to 100 micrometers.

History

By the early 1970s, astronomers began to consider the possibility of placing an infrared telescope above the obscuring effects of Earth's atmosphere. In 1979, a National Research Council of the National Academy of Sciences report, *A Strategy for Space Astronomy and Astrophysics for the 1980s*, identified a Space Infrared Telescope Facility (SIRTF) as "one of two major astrophysics facilities [to be developed] for Spacelab", a Shuttle-borne platform. Anticipating the major results from an upcoming Explorer satellite and from the Shuttle mission, the report also favored the "study and development of ... long-duration spaceflights of infrared telescopes cooled to cryogenic temperatures." The launch in January 1983 of the Infrared Astronomical Satellite, jointly developed by the United States, the Netherlands, and the United Kingdom, to conduct the first infrared survey of the sky, whetted the appetites of scientists worldwide for follow-up space missions capitalizing on the rapid improvements in infrared detector technology.

Earlier infrared observations had been made by both space-based and ground-based observatories. Ground-based observatories have the drawback that at infrared wavelengths or frequencies, both the Earth's atmosphere and the telescope itself will radiate (glow) strongly. Additionally, the atmosphere is opaque at most infrared wavelengths. This necessitates lengthy exposure times and greatly decreases the ability to detect faint objects. It could be compared to trying to observe the stars at noon. Previous space-based satellites (such as IRAS, the Infrared Astronomical Satellite, and ISO, the Infrared Space Observatory) were operational during the 1980s and 1990s and great advances in astronomical technology have been made since then.

Most of the early concepts envisioned repeated flights aboard the NASA Space Shuttle. This approach was developed in an era when the Shuttle program was expected to support weekly flights of up to 30 days duration. A May 1983 NASA proposal described SIRTF as a Shuttle-attached mission, with an evolving scientific instrument payload. Several flights were anticipated with a probable transition into a more extended mode of operation, possibly in association with a future space platform or space station. SIRTF would be a 1-meter class, cryogenically cooled, multi-user facility consisting of a telescope and associated focal plane instruments. It would be launched on the Space Shuttle and remain attached to the Shuttle as a Spacelab payload during astronomical observations, after which it would be returned to Earth for refurbishment prior to re-flight. The first flight was expected to occur about 1990, with the succeeding flights anticipated beginning approximately one year later. However, the Spacelab-2 flight aboard STS-51-F showed that the Shuttle environment was poorly suited to an onboard infrared telescope due to contamination from the relatively "dirty" vacuum associated with the orbiters. By September 1983 NASA was considering the "possibility of a long duration [free-flyer] SIRTF mission".

Spitzer is the only one of the Great Observatories not launched by the Space Shuttle, which had been originally intended. However after the 1986 Challenger disaster, the Centaur LH2/LOX upper stage, which would have been required to place it in its final orbit, was banned from Shuttle use. The mission underwent a series of redesigns during the 1990s, primarily due to budget considerations. This resulted in a much smaller but still fully capable mission which could use the smaller Delta II expendable launch vehicle.

Logo

One of the most important advances of this redesign was an Earth-trailing orbit. Cryogenic satellites that require liquid helium (LHe, T ≈ 4 K) temperatures in near-Earth orbit are typically exposed to a large heat load from the Earth, and consequently entail large usage of LHe coolant, which then tends to dominate the total payload mass and limits mission life. Placing the satellite in solar orbit far from Earth allowed innovative passive cooling such as the sun shield, against the single remaining major heat source to drastically reduce the total mass of helium needed, resulting in an overall smaller lighter payload, with major cost savings. This orbit also simplifies telescope pointing, but does require the Deep Space Network for communications.

The primary instrument package (telescope and cryogenic chamber) was developed by Ball Aerospace & Technologies Corp., in Boulder, CO. The individual instruments were developed jointly by industrial, academic, and government institutions, the principals being Cornell, the University of Arizona, the Smithsonian Astrophysical Observatory, Ball Aerospace, and Goddard Spaceflight Center. The spacecraft was built by Lockheed Martin. The mission is operated and managed by the Jet Propulsion Laboratory and the Spitzer Science Center, located on the Caltech campus in Pasadena, California.

Instruments

Spitzer has three instruments on-board:

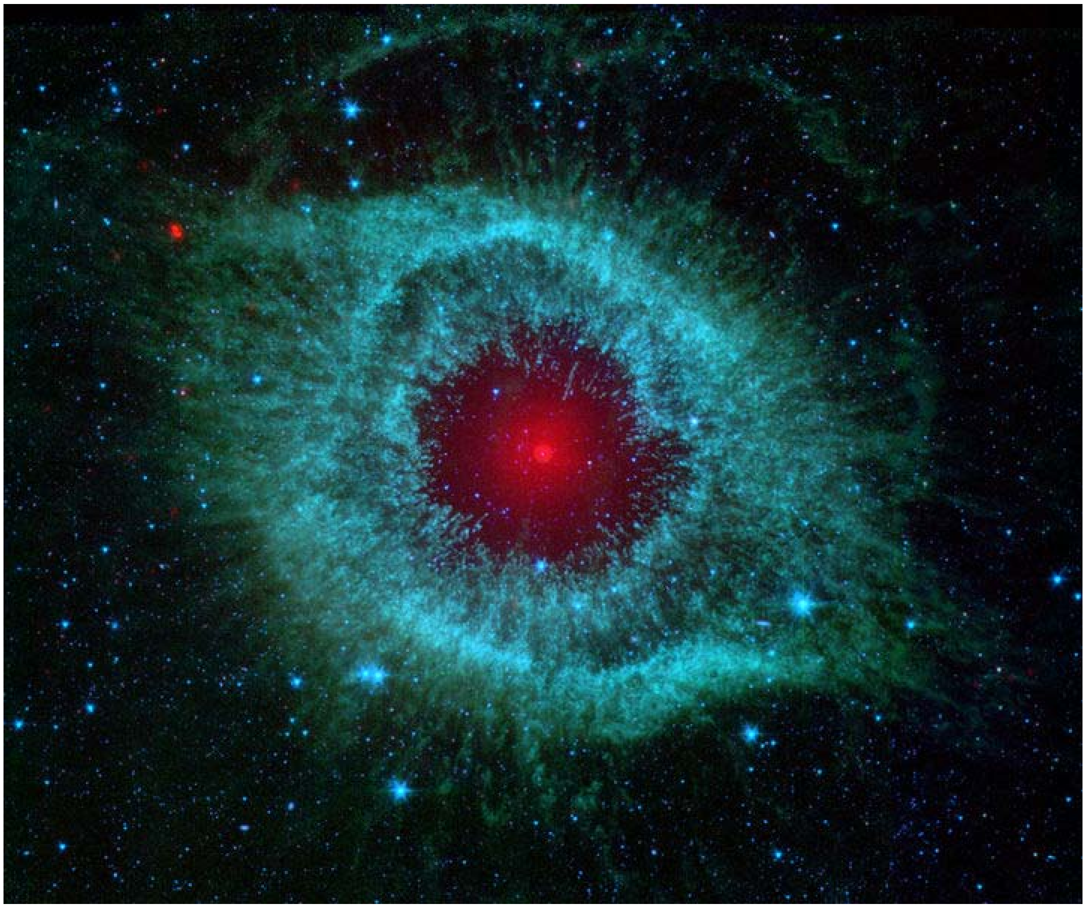
- IRAC (**I**nfra**r**ed **A**rray **C**amera), an infrared camera which operates simultaneously on four wavelengths (3.6 µm, 4.5 µm, 5.8 µm and 8 µm). Each module uses a 256 × 256 pixel detector—the short wavelength pair use indium antimonide technology, the long wavelength pair use arsenic-doped silicon impurity band conduction technology. The two shorter wavelength bands (3.6 um & 4.5 um) for this instrument remain productive after LHe depletion in the spring of 2009, at the telescope equilibrium temperature of around 30 K, so IRAC continues to operate as the "Spitzer Warm Mission".

- IRS (**I**nfra**r**ed **S**pectrograph), an infrared spectrometer with four sub-modules which operate at the wavelengths 5.3-14 µm (low resolution), 10-19.5 µm (high resolution), 14-40 µm (low resolution), and 19-37 µm (high resolution). Each module uses a 128x128 pixel detector—the short wavelength pair use arsenic-doped silicon blocked impurity band technology, the long wavelength pair use antimony-doped silicon blocked impurity band technology.

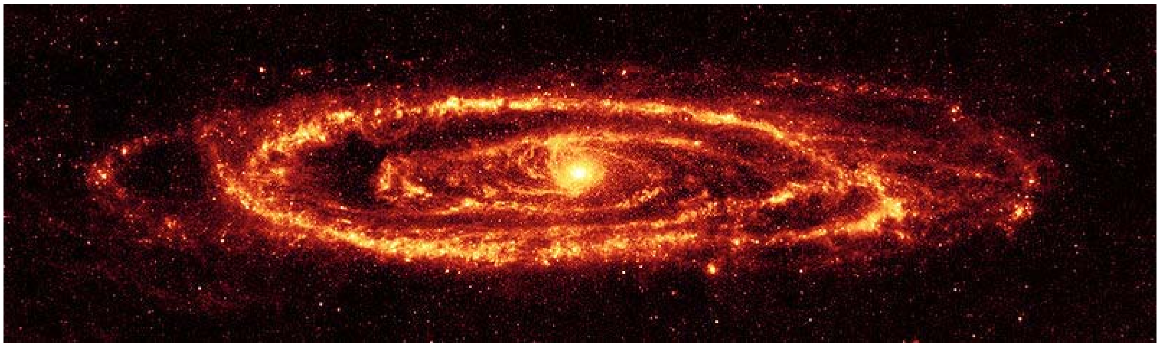
- MIPS (**M**ultiband **I**maging **P**hotometer for **S**pitzer), three detector arrays in the far infrared (128 × 128 pixels at 24 µm, 32 × 32 pixels at 70 µm, 2 × 20 pixels at 160 µm). The 24 µm detector is identical to one of the IRS short wavelength modules. The 70 µm detector uses gallium-doped germanium technology, and the 160 µm detector also uses gallium-doped germanium, but with mechanical stress added to each pixel to lower the bandgap and extend sensitivity to this long wavelength.

As an example of data from the different instruments, the nebula Henize 206 was imaged in 2004, allowing comparison of images from each device.

Results



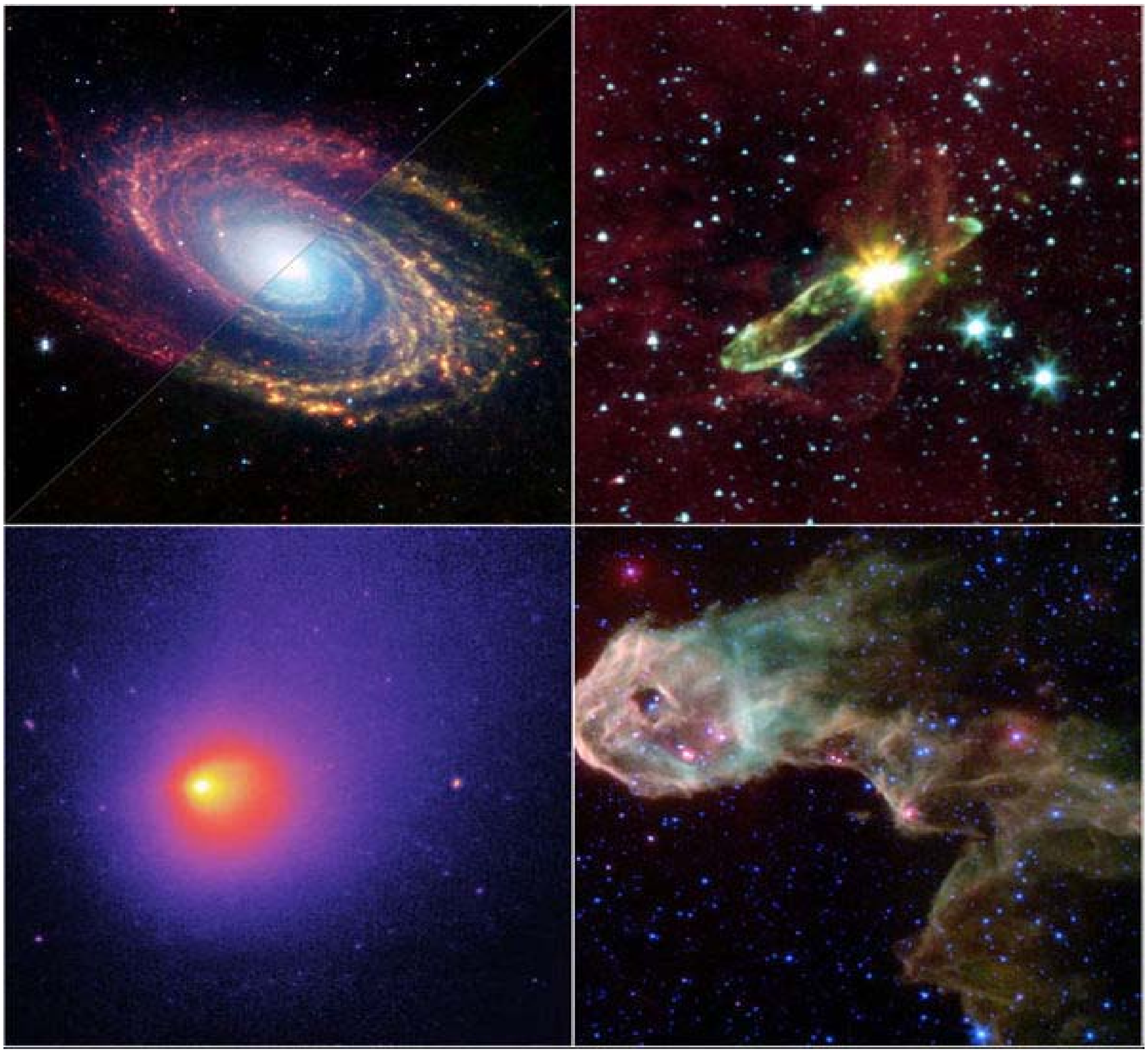
The Helix Nebula. Blue shows infrared light of 3.6 to 4.5 micrometers; green shows infrared light of 5.8 to 8 micrometers; and red shows infrared light of 24 micrometers.



The Andromeda Galaxy (M31) taken by Spitzer in infrared, MIPS, 24 micrometers 2004 August 25.

The first images taken by SST were designed to show off the abilities of the telescope and showed a glowing stellar nursery; a big swirling, dusty galaxy; a disc of planet-forming debris; and organic material in the distant universe. Since then, many monthly press releases have highlighted Spitzer's capabilities, as the NASA and ESA images do for the Hubble Space Telescope.

As one of its most noteworthy observations, in 2005, SST became the first telescope to directly capture the light from extrasolar planets, namely the "hot Jupiters" HD 209458b and TrES-1. (It did not resolve that light into actual images though.) This was the first time extrasolar planets had actually been visually seen; earlier observations had been indirectly made by drawing conclusions from behaviors of the stars the planets were orbiting. The telescope also discovered in April 2005 that Cohen-kuhi Tau/4 had a planetary disk that was vastly younger and contained less mass than previously theorized, leading to new understandings of how planets are formed.



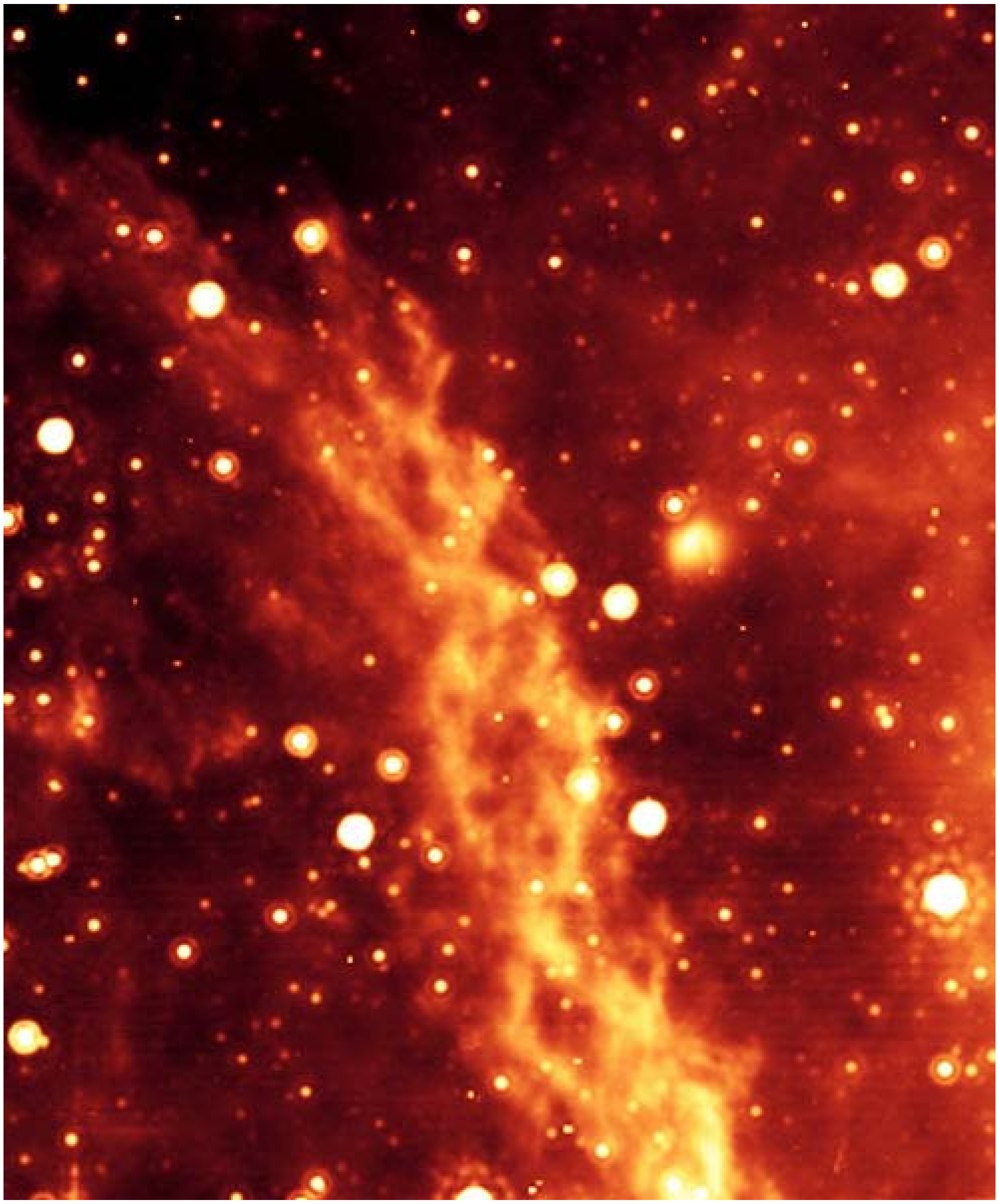
Clockwise from the upper-left: infrared views of spiral galaxy Messier 81; embedded outflows from Herbig-Haro 46/47 protostar; protostars uncovered in multiple views of dark globule in IC1396; and Comet Schwassmann-Wachmann 1.

While some time on the telescope is reserved for participating institutions and crucial projects, astronomers around the world also have the opportunity to submit proposals for observing time. Important targets include forming stars (young stellar objects, or YSOs), planets, and other galaxies. Images are freely available for educational and journalistic purposes.

In 2004, it was reported that Spitzer had spotted a faintly glowing body that may be the youngest star ever seen. The telescope was trained on a core of gas and dust known as L1014 which had previously appeared completely dark to ground-based observatories and to ISO (Infrared Space Observatory), a predecessor to Spitzer. The advanced technology of Spitzer revealed a bright red hot spot in the middle of L1014.

Scientists from the University of Texas at Austin, who discovered the object, believe the hot spot to be an example of early star development, with the young star collecting gas and dust from the cloud around it. Early speculation about the hot spot was that it might have been the faint light of another core that lies 10 times further from Earth but along the same line of sight as L1014. Follow-up observation from ground-based near-infrared observatories detected a faint fan-shaped glow in the same location as the object found by Spitzer. That glow is too feeble to have come from the more distant core, leading to the conclusion that the object is located within L1014. (Young *et al.*, 2004)

In 2005, astronomers from the University of Wisconsin at Madison and Whitewater determined, on the basis of 400 hours of observation on the Spitzer Space Telescope, that the Milky Way Galaxy has a more substantial bar structure across its core than previously recognized.



Artificial color image of the Double Helix Nebula, thought to be generated at the galactic center by magnetic torsion 1000 times greater than the sun's.

Also in 2005, astronomers Alexander Kashlinsky and John Mather of NASA's Goddard Space Flight Center reported that one of Spitzer's earliest images may have captured the light of the first stars in the universe. An image of a quasar in the Draco constellation, intended only to help calibrate the telescope, was found to contain an infrared glow after the light of known objects was removed. Kashlinsky and Mather are convinced that the numerous blobs in this glow are the light of stars that formed as early as 100 million years after the big bang, red shifted by cosmic expansion.

In March 2006, astronomers reported an 80-light-year-long nebula near the center of the Milky Way Galaxy, the Double Helix Nebula, which is, as the name implies, twisted into a double spiral shape. This is thought to be evidence of massive magnetic fields generated by the gas disc orbiting the supermassive black hole at the galaxy's center, 300 light years from the nebula and 25,000 light years from Earth. This nebula was discovered by the Spitzer Space Telescope, and published in the magazine *Nature* on March 16, 2006.

In May 2007, astronomers successfully mapped the atmospheric temperature of HD 189733 b, thus obtaining the first map of some kind of an extrasolar planet.

A cluster of new stars forming in the Serpens South cloud

Since September 2006 the telescope participates in a series of surveys called the Gould Belt Survey, observing the Gould's Belt region in multiple wavelengths. The first set of observations by the Spitzer Space Telescope were completed from September 21, 2006 through September 27. Resulting from these observations, the team of astronomers led by Dr. Robert Gutermuth, of the Harvard-Smithsonian Center for Astrophysics reported the discovery of Serpens South, a cluster of 50 young stars in the Serpens constellation.

In August 2009, the telescope found evidence of a high-speed collision between two burgeoning planets orbiting a young star.

In October 2009, astronomers published findings of the "Phoebe ring" of Saturn, which was found with the telescope; the ring is a huge, tenuous disc of material extending from 128 to 207 times the radius of Saturn.

GLIMPSE and MIPSGAL surveys

GLIMPSE, the Galactic Legacy Infrared Mid-Plane Survey Extraordinaire, is a survey spanning 300° of the inner Milky Way galaxy. It consists of approximately 444,000 images taken at 4 separate wavelengths using the Infrared Array Camera.

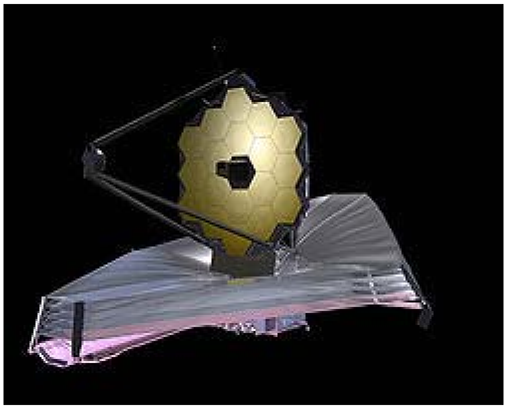
MIPSGAL is a similar survey covering 278° of the galactic disk at longer wavelengths.

On June 3, 2008, scientists unveiled the largest, most detailed infra-red portrait of the Milky Way, created by stitching together more than 800,000 snapshots, at the 212th meeting of the American Astronomical Society in St.Louis, Missouri.

Chapter- 11

James Webb Space Telescope

James Webb Space Telescope



Artist's impression of JWST. In normal working mode the mirror will be totally and permanently shaded from the sun by the radiation shield below.

General information

Organization	NASA / ESA / CSA
Major contractors	Northrop Grumman Ball Aerospace
Launch date	2014 or in 2015
Launched from	Guiana Space Centre ELA-3 Kourou, French Guiana
Launch vehicle	Ariane 5
Mission length	5 years (design) 10 years (goal)
Mass	6,200 kg (14,000 lb)

Orbit period	1 year
Location	1.5 million km from Earth (Lagrangian point L2)
Telescope style	Three Mirror Anastigmat
Wavelength	0.6 to 28 µm (infrared)
Diameter	~6.5 m (21 ft)
Collecting area	25 m^2 (270 sq ft)
Focal length	131.4 m (431 ft)
Instruments	
NIRCam	Near IR Camera
NIRSpec	Near IR Spectrograph
MIRI	Mid IR Instrument
FGS	Fine Guidance Sensor

The **James Webb Space Telescope** (**JWST**) is a planned infrared space observatory and is the scientific successor to the Hubble Space Telescope. The JWST or Webb Telescope's main scientific goal is to observe the most distant objects in the universe beyond the reach of either ground-based instruments or the Hubble. The JWST is a project of the National Aeronautics and Space Administration, the United States space agency, with international collaboration from the European Space Agency and the Canadian Space Agency, including contributions from fifteen nations.

Originally called the **Next Generation Space Telescope** (**NGST**), it was renamed in 2002 after NASA's second administrator James E. Webb (1906–1992). Webb had headed NASA from the beginning of the Kennedy administration through the Johnson administration (1961–68), thus overseeing all the manned launches in the Mercury through Gemini programs, until just before the first manned Apollo flight.

The JWST will orbit the Sun approximately 1,500,000 km (930,000 mi) on the far side of Earth at the L2 Lagrange point. Objects at the L2 point orbit the Sun in synchrony with the Earth, which allows the JWST to use one radiation shield, positioned between the telescope and the Earth, to protect it from the Sun's heat and light (and a small amount of additional infrared from the Earth, also). The telescope will be in a very large 800,000 km radius halo orbit around L2, and so will avoid any part of Earth's shadow. From the JWST's position, the Earth will be very close to the Sun's position but not eclipse it, while the Moon will show a tiny crescent phase during its maximum angular distance from the Sun.

Current plans call for the telescope to be launched on an Ariane 5 rocket in June 2014 (or mid 2015) on a five-year mission (10 year goal).

Mission

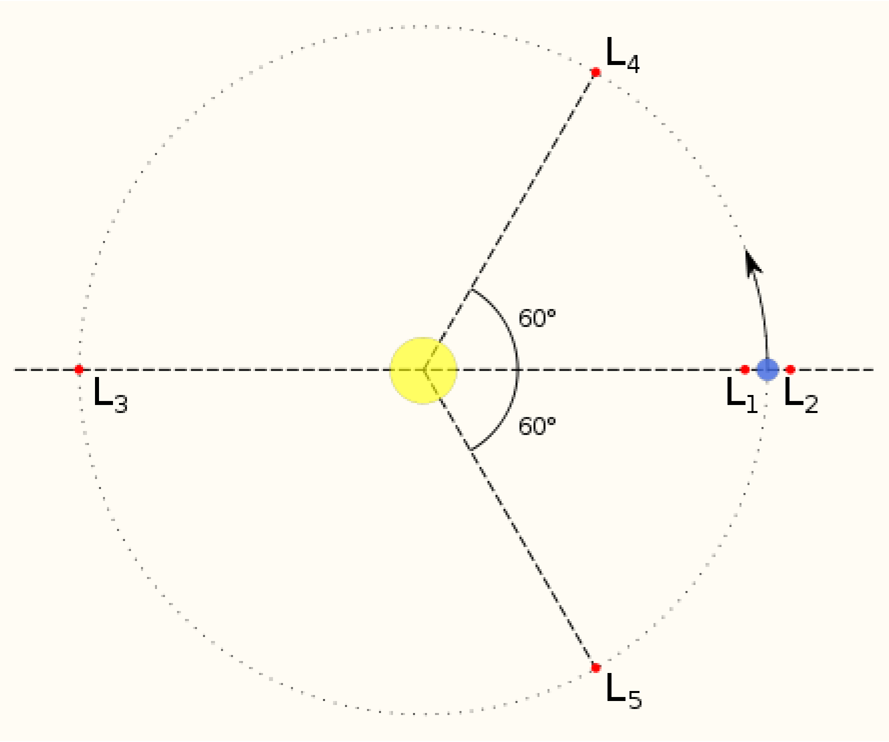
Full scale model on display at NASA Goddard

The JWST's primary scientific mission has four main components: to search for light from the first stars and galaxies which formed in the Universe after the Big Bang, to study the formation and evolution of galaxies, to understand the formation of stars and planetary systems and to study planetary systems and the origins of life. All of these jobs can be done more effectively by analyzing near-infrared light rather than light in the visible part of the spectrum. For this reason the JWST's instruments will not measure visible or ultraviolet light like the Hubble Telescope, but will have a much greater capacity to collect infrared light. In its present design, the JWST will detect a range of wavelengths from 0.6 (near the cutoff between red and near-infrared) to 28 micrometers (deep infrared radiation at about 100 kelvin).

Due to a combination of redshift, dust obscuration, and the low temperatures of many of the sources to be studied, the JWST must be able to measure infrared light with a very high degree of precision. To ensure that infrared emissions coming from the telescope or its instruments do not interfere with these observations, the entire observatory must operate at a very low temperature. Moreover, it must be well shielded from radiation coming from the Sun, the Earth and the Moon. To accomplish this, the JWST incorporates a large metalized fan-fold sunshield, which will unfurl to block infrared radiation and allow the telescope to radiatively cool, down to roughly 40 K (−230 °C, −390 °F). The telescope's location at the Sun-Earth L_2 Lagrange point ensures that the Earth and Sun occupy roughly the same relative position in the telescope's view and thus make the operation of this shield possible.

The observatory is due to be launched no earlier than June 2014 and is currently scheduled to be launched by an Ariane 5 from Guiana Space Centre Kourou, French Guiana into an L_2 orbit with a launch mass of approximately 6.2 tons. After a commissioning period of approximately six months the observatory will begin the science mission which is expected to last a minimum of five years. The potential for extension of the science mission beyond this period exists and the observatory is being designed accordingly.

Orbit



A diagram showing the five Lagrangian points of the Sun-Earth system. JWST will be located at L2, where the Earth and sun are directly behind it at all times.

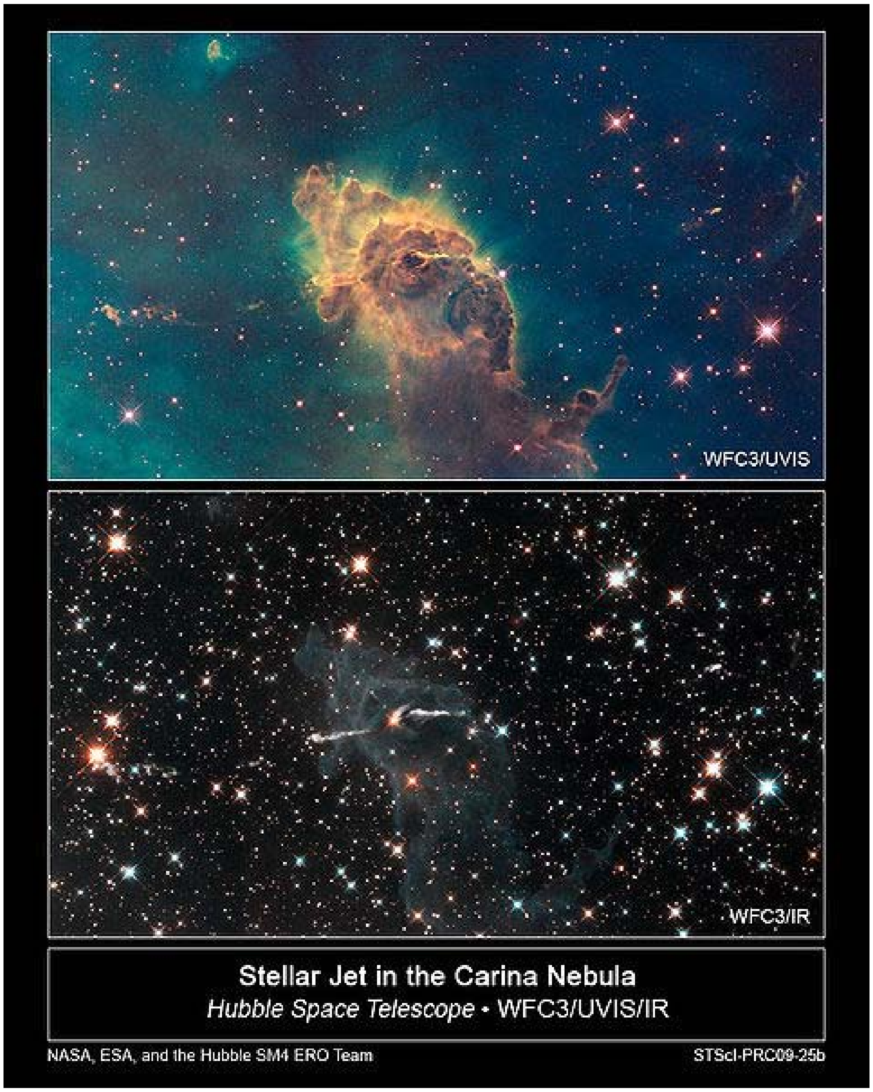
An idealized view from L2. A human observer exactly at L2 would only be able to see the blinding white annulus of the Sun, as the Sun disk is about 10% wider than the Earth disk. However, this image will never be seen from the actual position of the JWST, because its halo orbit around L2 is wide enough to keep the Earth (and Moon) from eclipsing the Sun at all.

The orbit of the JWST will be an elliptical orbit (with a radius of 800,000 km) around the semi-stable second Lagrange point, or L_2. The Earth-Sun L_2 point, about which the Webb telescope will orbit, is 1,500,000 kilometres (930,000 mi) from the Earth, nearly 4 times farther than the distance between the Earth to the moon. At such a great distance, the Webb telescope would be much more difficult to service after launch than the Hubble telescope; no plan contemplates doing so.

Normally, an object circling the Sun further out than the Earth would take more than one year to complete its orbit. However, the balance of gravitational pull at the L_2 point (in particular, the extra pull from Earth as well as the Sun) means that JWST will keep up with the Earth as it goes around the Sun. The combined gravitational forces of the Sun and the Earth can hold a spacecraft at this point, so that in theory it takes no rocket thrust to keep a spacecraft in orbit around L_2. In reality, the stable point is comparable to that of a ball balanced upon a saddle shape. Along one direction any perturbation will drive the ball toward the stable point, while in the crossing direction the ball, if disturbed, will fall away from the stable point. Thus some station-keeping is required, but with little energy expended - only 2-4 m/s per year, from the total budget of 150 m/s.

Since the JWST must be kept very cold to make accurate observations of distant astronomical objects, it has been designed with a large sunshield that blocks light and heat from the Sun. In order for such a shield to work properly, the sun's rays must be constantly coming from the same direction. To achieve this outcome, JWST will be put into a relatively large "halo orbit" around L_2. From the L_2 point itself, the Earth eclipses 90% of the disk of the Sun at all times and neither one appears to move at all, though lateral movement of the moon can be seen. However, the radius of the Webb telescope's orbit around L_2 will be so large that neither the Earth nor moon will eclipse the Sun, allowing the shield to deal with a relatively constant sunlight environment. This was considered to be more important than attempting to utilize the Earth's shadow to block some of the sunlight, in an orbit nearer the exact L2 point.

Optics



Two alternate Hubble Space Telescope views of the Carina Nebula, comparing visible (top) and infrared (bottom) astronomy

Infrared reveals more stars

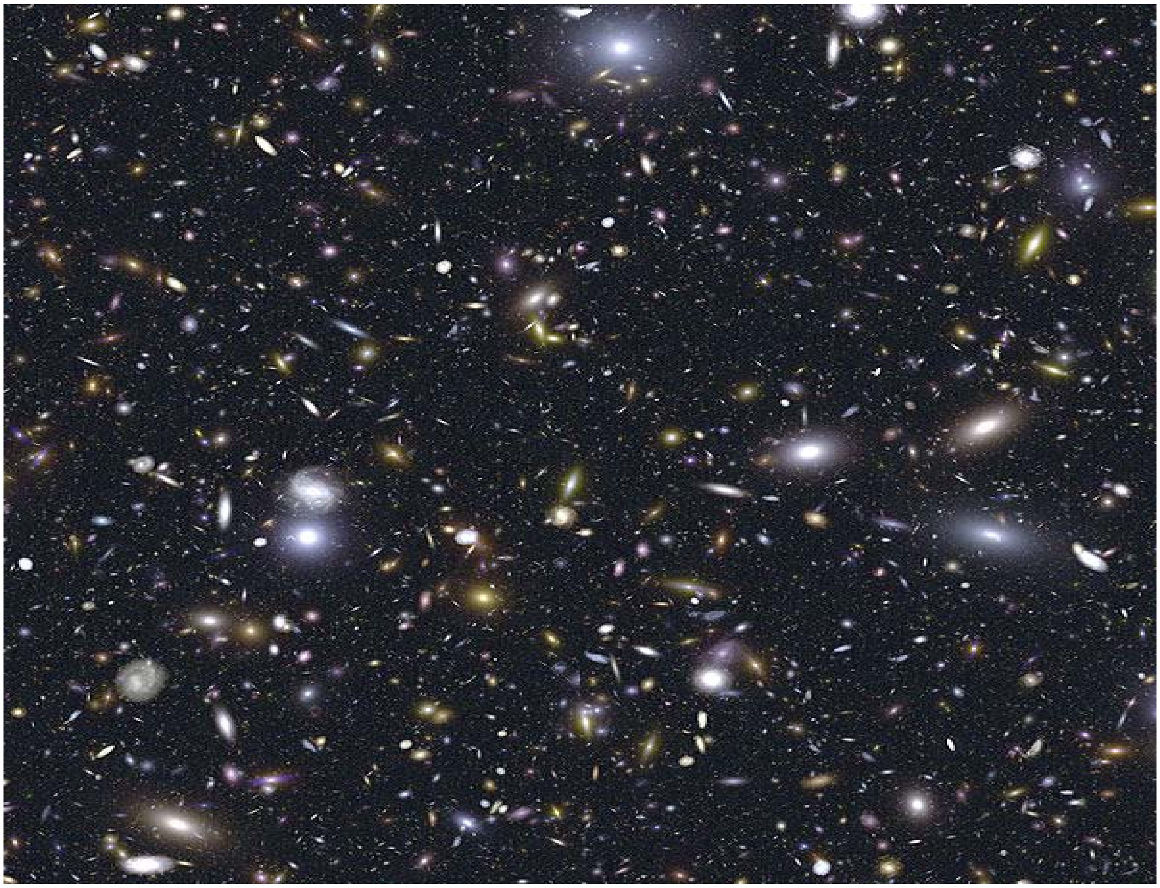
JWST is a true successor to the Hubble Space Telescope (HST) in that it will be able to see many more and much older stars. Compare the two images of the Carina Nebula taken with the HST (left margin). Though both images are of the same astronomical object taken by HST, the top image was photographed utilizing the visible spectrum, whereas the bottom image was taken in the infrared, using the HST's WFC3 upgrade. Notice how more stars can be counted almost anywhere in the bottom image (infrared spectrum) than in the same corresponding location of the top image (visible spectrum).

Visible spectrum views cannot peer through much of the gas and dust that may obscure an image like infrared views can. Almost all of the gas and dust obscuring images in visible spectrum views may entirely disappear if viewed in the infrared, so that the stars lying behind the gas and dust become easier to see. Infrared astronomy can penetrate dusty regions of space (such as molecular clouds), detect objects such as planets, and also view highly red-shifted objects from the early days of the universe.

The most distant stars in view are also the "youngest," that is, they were formed during a time period closer in time to that of the Big Bang than those stars less distant to us, such as our Sun. Because the universe is expanding, the light reaching us from those younger stars becomes red-shifted and are therefore easier to see if viewed in the infrared.

Infrared light is also useful for observing the cores of active galaxies which are often cloaked in gas and dust.

JWST optical design



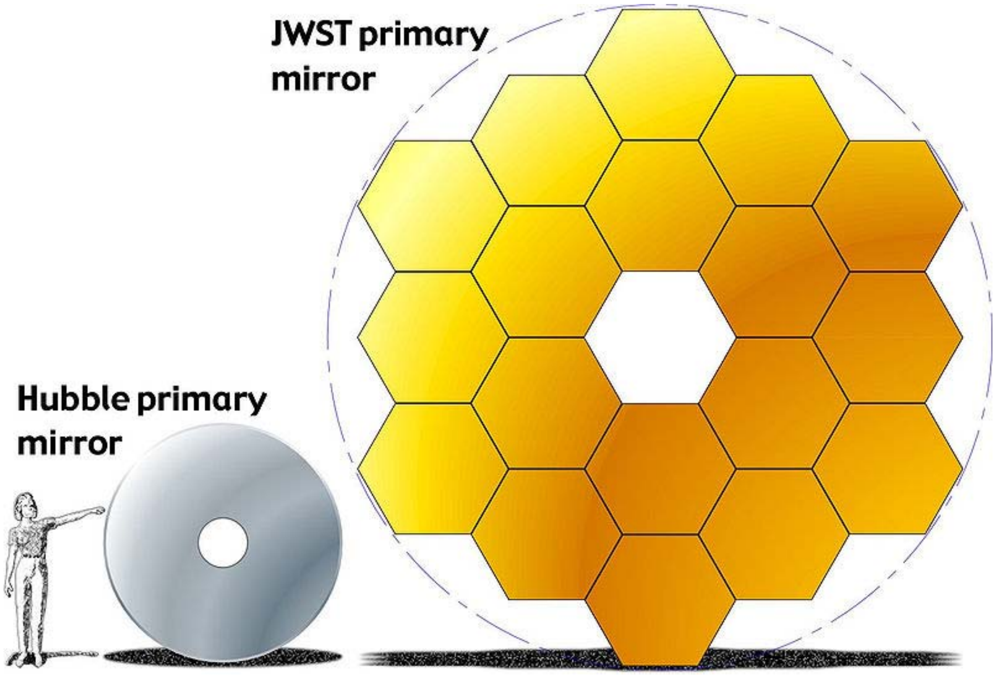
A simulation of JWST's performance. This shows a "typical" JWST image, based on the expected density of sources of different types, and the predicted JWST performance. It is a false-color image, since the JWST observes in the infrared.

Although JWST has a planned mass half that of the Hubble, its primary mirror (a 6.5 meter diameter gold-coated beryllium reflector) has a collecting area which is almost six times larger. As this diameter is much larger than any current launch vehicle, the mirror is composed of 18 hexagonal segments, which will unfold after the telescope is launched. These mirrors are currently being developed by Axsys Technologies in Cullman, Alabama. Sensitive micromotors and a wavefront sensor will position the mirror segments in the correct location, but subsequent to this initial configuration they will only rarely be moved. This process is much like an initial calibration, unlike terrestrial telescopes like the Keck which continually adjust their mirror segments using active optics to overcome the effects of gravitational and wind loading.

Ball Aerospace & Technologies Corp. is the principal optical subcontractor for the JWST program, led by prime contractor Northrop Grumman Aerospace Systems, under a contract from the NASA Goddard Space Flight Center, in Greenbelt, Maryland. Seventeen additional primary mirror segments, secondary, and tertiary mirrors, plus flight spares, will be delivered to Ball Aerospace from its beryllium mirror manufacturing team that includes Axsys, Brush Wellman, and Tinsley Laboratories. As each additional mirror is delivered to Ball Aerospace over the next year (to 2010), it will be mounted onto a lightweight, actuated strong-back assembly and undergo functional and environmental testing.

NASA has indicated that they will be incorporating microshutters, each about 100 by 200 micrometers, into the optics of the James Webb Space Telescope's Near InfraRed Spectrograph. An array of 62,000 of the shutters will sit in front of the spectrograph's 8-megapixel infrared detector. The microshutters will create an effect similar to a human eye squinting. When one squints, one's eyelashes block light; in the same way, the microshutters allow the telescope to focus on the faint light of stars and galaxies even if they are adjacent to brighter objects.

Program status



Comparison with Hubble primary mirror

The JWST program is in the final design and fabrication phase (Phase C). As is typical for a complex design that cannot be changed once launched, there are detailed reviews of every portion of design, construction, and proposed operation.

In April 2006 the program was independently reviewed following a replanning phase begun in August 2005. The review concluded the program was technically sound, but that funding phasing at NASA needed to be changed. NASA has rephased its JWST budgets accordingly. The August 2005 replanning was necessitated by the cost growth revealed in Spring 2005. The primary technical outcomes of the replanning are significant changes in the integration and test plans, a 22-month launch delay (from 2011 to 2013), and elimination of system level testing for observatory modes at wavelength shorter than 1.7 micrometers. Other major features of the observatory are unchanged following the replanning efforts.

As of the 2005 re-plan, the life-cycle cost of the project was estimated at about US$4.5 billion. This comprises approximately US$3.5 billion for design, development, launch and commissioning, and approximately US$1.0 billion for ten years of operations. ESA is contributing about €300million, including the launch, and the Canadian Space Agency about $39M Canadian. As of May 2007 costs were still on target, but by 2010 cost over-runs were impacting other programs, though JWST itself remains on schedule.

In January 2007 nine of the ten technology development items in the program successfully passed a non-advocate review. These technologies were deemed sufficiently mature to retire significant risks in the program. The remaining technology development item (the MIRI cryocooler) completed its technology maturation milestone in April 2007. This technology review represented the beginning step in the process that ultimately moved the program into its detailed design phase (Phase C).

In March 2008, the project successfully completed its Preliminary Design Review (PDR). In April 2008, the project passed the Non-Advocate Review. Other passed reviews include the Integrated Science Instrument Module review in March 2009, the Optical Telescope Element review completed in October 2009, and the Sunshield review completed in January 2010.

In April 2010, the telescope passed the overall Mission Critical Design Review (MCDR). Passing the MCDR signified the integrated observatory will meet all science and engineering requirements for its mission. The MCDR encompassed all previous design reviews. The project schedule will undergo a review during the months following the MCDR. The spacecraft design, which passed a preliminary review in 2009, will continue toward final approval in 2011.

Construction and engineering

Six of the James Webb Space Telescope beryllium mirror segments undergoing a series of cryogenic tests at the X-ray & Cryogenic Facility at NASA's Marshall Space Flight Center in Huntsville, Alabama

NASA's Goddard Space Flight Center in Greenbelt, Maryland, is leading the management of the observatory project. The project scientist for the James Webb Space Telescope is John C. Mather. Northrop Grumman Aerospace Systems serves as the primary contractor for the development and integration of the observatory. They are responsible for developing and building the spacecraft element, which includes both the spacecraft bus and sunshield. Ball Aerospace has been subcontracted to develop and build the Optical Telescope Element (OTE). Goddard Space Flight Center is also responsible for providing the Integrated Science Instrument Module (ISIM).

The ISIM contains four science instruments. NIRCam (Near InfraRed Camera) is an infrared imager which will have a spectral coverage ranging from the edge of the visible (0.6 micrometers) through the Near Infrared (5 micrometers). The NIRCam will also serve as the observatory's wavefront sensor, which is required for wavefront sensing and control activities. The NIRCam is being built by a team led by the University of Arizona, with Principal Investigator Marcia Rieke. The industrial partner is Lockheed-Martin's Advanced Technology Center located in Palo Alto, California.

The James Webb Space Telescope's Engineering Design Unit (EDU) primary mirror segment, coated with gold

In addition to the Near Infrared (NIR) imaging capabilities of the NIRCam, the observatory will also perform spectrography over this range with the NIRSpec (Near InfraRed Spectrograph). NIRSpec is being built by the European Space Agency at ESTEC in Noordwijk, the Netherlands, leading a team involving EADS Astrium, Ottobrunn, and Friedrichshafen, Germany, and the Goddard Space Flight Center: the NIRSpec project scientist is Peter Jakobsen. The NIRSpec design provides 3 observing modes: a low resolution mode using a prism, an R~1000 multi-object mode and an R~2700 integral field unit or long-slit spectroscopy mode. Switching of the modes is done by operating a wavelength preselection mechanism called Filter Wheel Assembly and selecting a correspondent dispersive element (prism or grating) using the Grating Wheel Assembly mechanism. Both mechanisms are based on the successful ISOPHOT wheel mechanisms of the Infrared Space Observatory. The mechanisms and their optical elements are being designed, integrated and tested by Carl Zeiss Optronics GmbH of Oberkochen, Germany, under contract from Astrium.

The mid-IR wavelength range will be measured by the MIRI (Mid InfraRed Instrument), which contains both a mid-IR camera and spectrometer that has a spectral range extending from 5 to 27 micrometers. MIRI is being developed as a collaboration between NASA and a consortium of European countries, and is led by George Rieke (University of Arizona) and Gillian Wright (UK Astronomy Technology Centre, Edinburgh, part of the Science and Technology Facilities Council (STFC)). MIRI features similar wheel mechanisms as NIRSpec which are also developed and built by Carl Zeiss Optronics GmbH under contract from the Max Planck Institute for Astronomy, Heidelberg.

The FGS (Fine Guidance Sensor), led by the Canadian Space Agency under project scientist John Hutchings (Herzberg Institute of Astrophysics, National Research Council of Canada), is used to stabilize the line-of-sight of the observatory during science observations and also includes a Tunable Filter module for astronomical narrow-band imaging in the 1.5 to 5 micrometer wavelength range. The infrared detectors for both the NIRCam and NIRSpec modules are being provided by Teledyne Imaging Sensors (formerly Rockwell Scientific Company).

NASA is considering plans to add a grapple feature so future spacecraft might visit the observatory to fix gross deployment problems, such as a stuck solar panel or antenna. However, the telescope itself would not be serviceable, so that astronauts would not be able to perform tasks such as swapping instruments, as with the Hubble Telescope. Final approval for such an addition was to be considered as part of the Preliminary Design Review in March 2008.

Most of the data processing on the telescope is done by conventional single board computers. The conversion of the analog science data to digital form is performed by the custom-built SIDECAR ASIC (**S**ystem for **I**mage **D**igitization, **E**nhancement, **C**ontrol **A**nd **R**etrieval **A**pplication **S**pecific **I**ntegrated **C**ircuit). It is said that the SIDECAR ASIC will include all the functions of a 20-pound instrument box in a package the size of a half-dollar, and consume only 11 milliwatts of power. Since this conversion must be done close to the detectors, on the cool side of the telescope, the low power use of this IC will be important for maintaining the low temperature required for optimal operation of the JWST.

Ground support

The Space Telescope Science Institute (STScI) in Baltimore, Maryland has been selected as the Science and Operations Center (S&OC) for JWST. In this capacity, STScI will be responsible for the scientific operation of the telescope and delivery of data products to the astronomical community.

Public displays

In May 2007, a full-scale model of the telescope was assembled for display at the Smithsonian's National Air and Space Museum on the National Mall, Washington DC. The model was intended to give the viewing public a better understanding of the size, scale and complexity of the satellite. The model is significantly different from the telescope, as the model must withstand gravity and weather, so is constructed mainly of aluminum and steel measuring approximately 24 m (79 ft) x 12 m (39 ft) x 12 m (39 ft) and weighs 5.5 tonnes (12,000 lb).

The model has been on display at various places since 2005: Seattle, Washington; Colorado Springs, Colorado; Paris, France; Greenbelt, Maryland; Rochester, New York; Orlando, Florida; Dublin, Ireland; Montreal, Canada; Hatfield, United Kingdom; Munich, Germany; and Manhattan, New York. The model was built by the main contractor, Northrop Grumman Aerospace Systems.

Most recently, the model was on ongoing display in New York City's Battery Park during the 2010 World Science Festival. It served as the backdrop for a panel discussion featuring Nobel Prize laureate John C. Mather, astronaut John Grunsfeld and astronomer Heidi Hammel, which was followed by a star party hosted by Neil deGrasse Tyson, the director of the city's Hayden Planetarium.

Chapter- 12

Wide-field Infrared Survey Explorer

Wide-field Infrared Survey Explorer (WISE)

WISE is prepared for its mission into orbit

General information

NSSDC ID	2009-071A
Organization	NASA/JPL
Major contractors	Ball Aerospace Lockheed Martin Space Dynamics Laboratory SSG Precision Optronics, Inc.

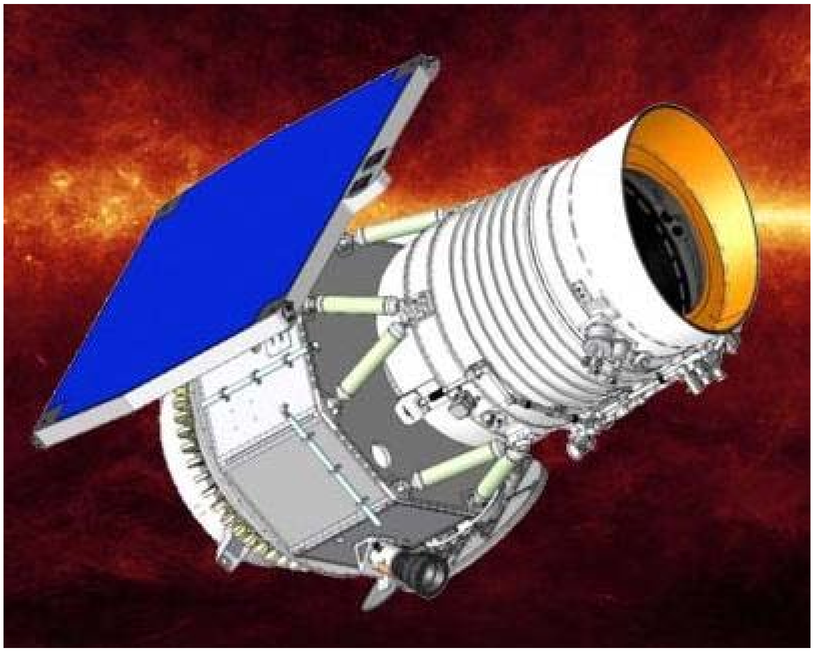
Launch date	2009-12-14 14:09:33 UTC
Launched from	Space Launch Complex 2W Vandenberg Air Force Base Lompoc, California
Launch vehicle	Delta II 7320-10
Mass	750 kg (1,650 lb)
Type of orbit	Sun-synchronous polar Inclination: 97.5°
Orbit height	525 km (326 mi)
Orbit period	95 minutes, 15 times per day
Location	Low Earth Orbit
Wavelength	3.4, 4.6, 12, 22 μm
Diameter	0.4 m

Wide-field Infrared Survey Explorer (WISE) is a NASA infrared-wavelength astronomical space telescope launched on 14 December 2009, and put into hibernation February 1, 2011. The US$320 million mission launched an Earth-orbiting satellite with a 40 cm (16 in) diameter infrared telescope, which performed an all-sky astronomical survey with images in 3, 5, 12 and 22 μm wavelength range bands, over 10 months. The initial mission length was limited by its hydrogen coolant, but a secondary post-crygenic mission continued for four more months.

By October 2010 WISE hydrogen coolant and original NASA funding ran out, and the proposed WISE warm mission, using remaining functionality, was not approved by NASA. Rather than abandon the spacecraft, the NASA Planetary division stepped in with funding for a shorter fourth month mission extension called NEOWISE, to search for small solar system bodies close to Earth's orbit.

WISE served as a replacement for the Wide Field Infrared Explorer (WIRE), which failed within hours of reaching orbit in March 1999. In certain measurements, WISE is over 1,000 times more sensitive than prior infrared space surveys such as IRAS, AKARI, and COBE's DIRBE. The principal investigator for WISE, said the telescope found dozens of previously unknown asteroids every day. Overall, over 33,500 new asteroids and comets were discovered, and over 154,000 solar system objects were observed by WISE as of October 2010.

Planned goals



Artist's concept of the Wide-field Infrared Survey Explorer

The mission was planned to create infrared images of 99% of the sky, with at least eight images made of each position on the sky in order to increase accuracy. The spacecraft was placed in a 525 km (326 mi), circular, polar, sun-synchronous orbit for its 10 month mission, during which it has taken 1.5 million images, one every 11 seconds. The satellite orbited above the terminator, its telescope pointing always to the opposite direction to the Earth (except for pointing towards the Moon, it was avoided), and its solar cells towards the Sun. Each image covers a 47-arcminute field of view, which means a 6 arcsecond resolution. Each area of the sky was scanned at least 10 times (at the equator, the poles were scanned at theoretically every revolution due to the overlapping of the images). The produced image library contains data on the local Solar System, the Milky Way Galaxy, and the more distant universe. Among the objects WISE studied are asteroids, cool, dim stars such as brown dwarfs, and the most luminous infrared galaxies.

Targets outside the Solar system

Stellar nurseries, which are covered by interstellar dust, are detectable in infrared, since at this wavelength electromagnetic radiation can penetrate the dust. Thus galaxies of the young Universe and interacting galaxies, where star formation is intensive, are bright in infrared. On this wavelength the interstellar gas clouds are also detectable, as well as protoplanetary discs, out of them it was expected to discover some thousand.

Targets within the Solar system

WISE wasn't able to detect Kuiper belt objects, as their temperature is too low. It was able to detect any objects warmer than 70-100 Kelvins. A Neptune-sized object would be detectable out to 700 AU, a Jupiter-mass object out to one light year (63,000 AU), where it would still be within the Sun's zone of gravitational control. A larger object of 2–3 Jupiter masses would be visible at a distance of up to seven to ten light years.

At the time of planning, it was estimated that WISE would detect about 300,000 main-belt asteroids, of which approximately 100,000 will be new, and some 700 near-Earth objects including about 300 undiscovered. That translates to ~1000 new Main-belt asteroids per day, and 1-3 NEOs per day. The peak of magnitude distribution for NEOs will be about 21-22 V. WISE would detect each typical Solar system object 10-12 times over about 36 hours with the interval of 3 hours.

Construction of the WISE telescope was divided between Ball Aerospace & Technologies (spacecraft, operations support), SSG Precision Optronics, Inc. (telescope, optics, scan mirror), DRS and Rockwell (focal planes), Lockheed Martin (cryostat, cooling for the telescope), and Space Dynamics Laboratory (instruments, electronics, and testing). The program is managed through the Jet Propulsion Laboratory.

Spacecraft

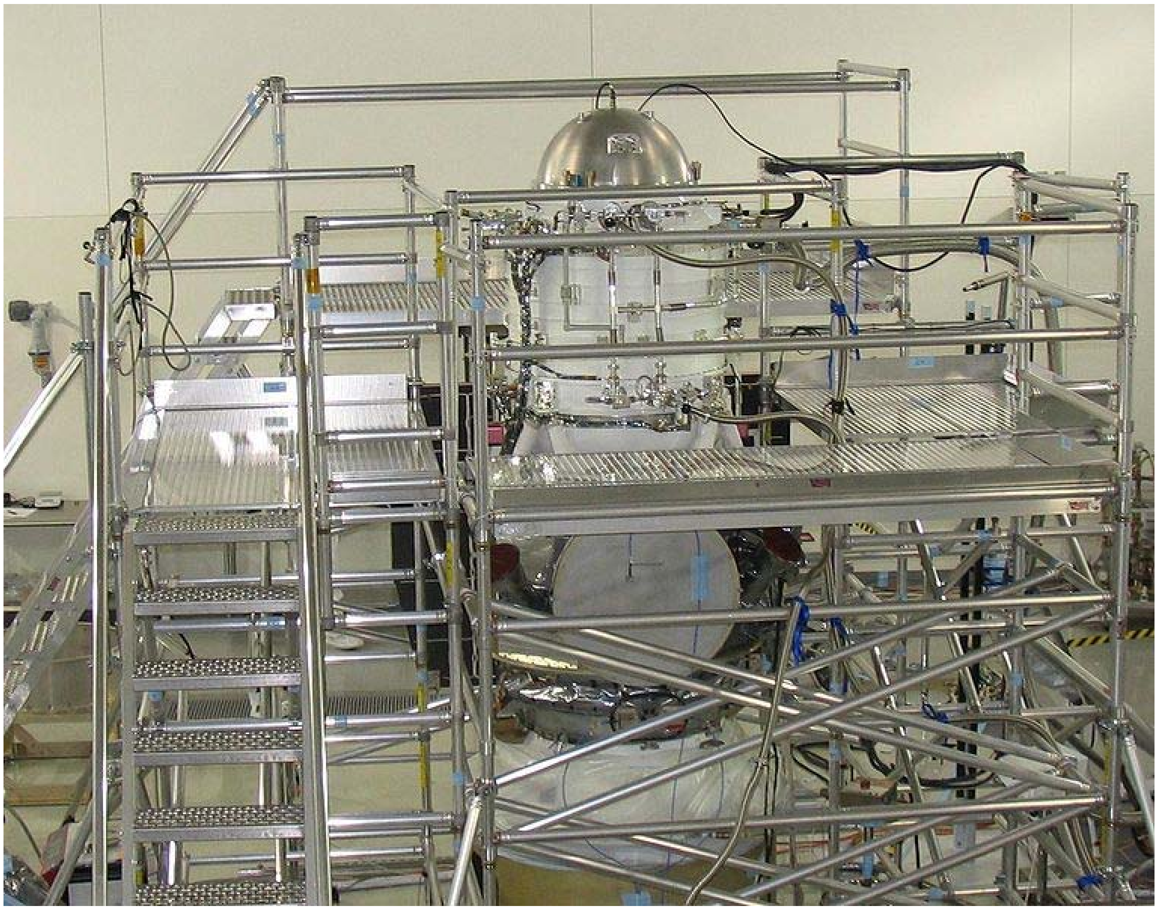
The WISE spacecraft was built by Ball Aerospace and Technologies Corp. in Boulder, Colorado. The spacecraft is derived from the Ball Aerospace RS-300 spacecraft architecture, particularly the NEXTSat spacecraft built for the successful Orbital Express mission launched on March 9, 2007. The flight system has an estimated mass of 560 kg (1,200 lb). The spacecraft is three-axis stabilized, with body-fixed solar arrays. It uses a high-gain antenna in the K_u band to transmit to the ground through the TDRSS geostationary system. Ball also performed the testing and flight system integration.

Mission

WISE surveyed the sky in four wavelengths of the infrared band, at a very high sensitivity. Its detector arrays have 5-sigma sensitivity limits of 120, 160, 650, and 2600 microjanskies (µJy) at 3.3, 4.7, 12, and 23 micrometres (aka microns). This is a factor of 1,000 times better sensitivity than the survey completed in 1983 by the IRAS satellite in the 12 and 23 micrometre bands, and a factor of 500,000 times better than the 1990s survey by the Cosmic Background Explorer (COBE) satellite at 3.3 and 4.7 micrometres. On the other hand, IRAS could also observe 60 and 100 micron wavelengths, which WISE does not.

- Band 1 – 3.4 micrometres (microns) — broad-band sensitivity to stars and galaxies

- Band 2 – 4.6 micrometres — detect thermal radiation from the internal heat sources of sub-stellar objects like brown dwarfs
- Band 3 – 12 micrometres — detect thermal radiation from asteroids
- Band 4 – 22 micrometres — sensitivity to dust in star-forming regions (material with temperatures of 70–100 kelvins)



A scaffolding structure built around WISE allowed engineers to freeze its hydrogen coolant

The primary mission lasts ten months: one month for checkout, six months for a full-sky survey, then an additional three months of survey until cryogenic coolant runs out. The partial second survey pass will facilitate the study of changes (e.g. orbital movement) in observed objects.

Congressional Hearing

On November 8, 2007, the House Committee on Science and Technology's Subcommittee on Space and Aeronautics held a hearing to examine the status of NASA's Near-Earth Object (NEO) survey program. The prospect of using WISE was proposed by NASA officials.

NASA officials told Committee staff that NASA plans to use WISE to detect near-Earth objects in addition to performing its science goals. It was projected that WISE could detect 400 NEOs (or roughly 2 percent of the estimated NEO population of interest) within its one-year mission.

Results

By May 27, 2010, WISE discovered 12,141 previously unknown asteroids, of which 64 were considered near-Earth, and 11 new comets. This grew to 113 near-Earth asteroids and 16 comets by August 26, 2010. Two unambiguous brown dwarfs have been detected, although their distances are unknown, as well as some brown dwarf candidates.

By October 2010, over 33,500 new asteroids and comets were discovered, and nearly 154,000 solar system objects were observed by WISE. Out of this total on that date, 136 new NEA, PHA, & Comets were discovered. Out of these, 19 were new potentially hazardous asteroids, celestial objects both more likely to hit Earth and cause significant destruction (not to be confused with the more common but less dangerous Near Earth object (NEO)). As of Oct 2010, there are 1,151 PHA are known, including those found by WISE.

Discovery of an ultra-cool brown dwarf, WISEPC J045853.90+643451.9, about 10 to 20 light years away from Earth, was announced in late 2010 (from early data).

Project milestones

The WISE Mission is led by Dr. Edward L. Wright of the University of California, Los Angeles. The mission has a long history under Wright's efforts, and was first funded by NASA in 1999 as a candidate for a NASA Medium-class Explorer (MIDEX) mission under the name *Next Generation Sky Survey* (NGSS). The history of the program from 1999 to date is briefly summarized as follows:

- January 1999 — NGSS is one of five missions selected for a Phase A study, with an expected selection in late 1999 of two of these five missions for construction and launch, one in 2003 and another in 2004. Mission cost is estimated at $139 million at this time.
- March 1999 — WIRE infrared telescope spacecraft fails within hours of reaching orbit.
- October 1999 — Winners of MIDEX study are awarded, and NGSS is not selected.
- October 2001 — NGSS proposal is re-submitted to NASA as a MIDEX mission.
- April 2002 — NGSS proposal is accepted by the NASA Explorer office to proceed as one of four MIDEX programs for a Pre-Phase A study.
- December 2002 — NGSS changes its name to *Wide-field Infrared Survey Explorer* (WISE).

- March 2003 — NASA releases a press release announcing WISE has been selected for an Extended Phase-A study, leading to a decision in 2004 on whether to proceed with the development of the mission.
- April 2003 — Ball Aerospace is selected as the spacecraft provider for the WISE mission.
- April 2004 — WISE is selected as NASA's next MIDEX mission. WISE's cost is estimated at $208 million at this time.
- November 2004 — NASA selects the Space Dynamics Laboratory at Utah State University to build the telescope for WISE.
- October 2006 — WISE is confirmed for development by NASA and authorized to proceed with development. Mission cost at this time is estimated to be $300 million.
- 14 December 2009 — WISE successfully launched from Vandenberg Air Force Base, California.
- 29 December 2009 — WISE successfully jettisoned instrument cover.
- 6 January 2010 — WISE first light image released.
- 14 January 2010 — WISE begins its regular four wavelength survey scheduled for nine months duration. It is expected to cover 99% of the sky with overlapping images in the first 6 months and continuing with a second pass until the hydrogen coolant is exhausted about three months later.
- 25 January 2010 — WISE detects a never-before-seen near earth asteroid, designated 2010 AB78.
- 11 February 2010 — WISE detects a previously unknown comet, designated P/2010 B2 (WISE).
- 25 February 2010 — WISE website reports it has surveyed over a quarter of the sky to a depth of 7 overlapping image frames.
- 10 April 2010 — WISE website reports it has surveyed over half of the sky to a depth of 7 overlapping image frames.
- 26 May 2010 — WISE website reports it has surveyed over three-quarters of the sky to a depth of 7 overlapping image frames.
- 16 July 2010 — press release announces that total sky coverage will be completed on 17 July 2010. About half of the sky will be mapped again before the instrument's block of solid hydrogen coolant is exhausted.
- October 2010 — WISE hydrogen coolant runs out. Start of NASA Planetary Division funded NEOWISE mission.
- January 2011 — Entire sky surveyed to an image density of at least 16+ frames (ie. second scan of sky completed).
- February 1, 2011 — WISE is put into hibernation.

Status

The launch of the Delta II rocket carrying the WISE spacecraft was originally scheduled for December 11, 2009. This attempt was scrubbed to correct a problem with a booster rocket steering engine. The launch was then rescheduled for December 14, 2009. The second attempt launched on time at 14:09:33 UTC (06:09 local PST) from Vandenberg

Air Force Base in California. The rocket successfully placed the WISE spacecraft into the planned polar orbit at an altitude of 326 miles (525 km) above the Earth.

The WISE spacecraft underwent a month long checkout after launch, which found all spacecraft systems functioning normally and both the low and high rate data links to the operations center working properly. The instrument cover was successfully jettisoned on December 29, 2009. The first light image from WISE was released on January 6, 2010. It was an eight-second exposure taken in the direction of the Carina constellation showing infrared light in false color from three of WISE's four wavelength bands: Blue, green and red corresponding to 3.4, 4.6, and 12 micrometres, respectively. On January 14, 2010, the WISE mission started its official sky survey. A planned release of survey data (as an overlapping set of 4 megapixel images) is expected in early 2011. The WISE group's bid for continued funding for an extended "warm mission" was recently scored low by a NASA review board, in part because of a lack of outside groups publishing on WISE Data. Such a mission would have allowed use of the 3.4 and 4.6 micrometre detectors after the last of cryo-coolant had been exhausted, with the goal of completing a second sky survey to detect additional objects and obtain parallax data on putative brown dwarf stars. Rather than see the 320 million dollar spacecraft abandoned, the NASA Planetary Division stepped in as an alternate source of funding in October 2010.

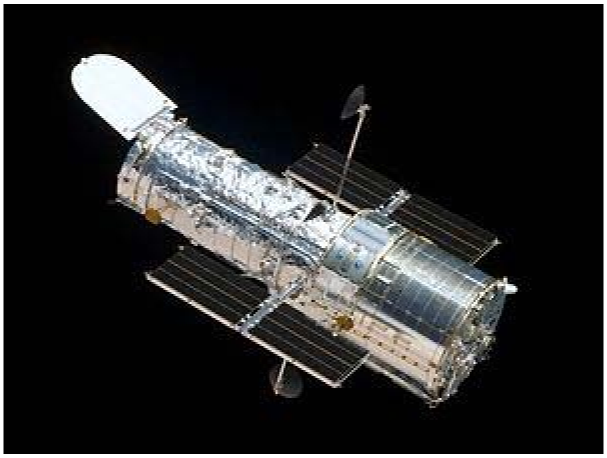
NEOWISE

In October 2010, the NASA Planetary Division saved the spacecraft from termination with a 400k USD one month program extension called "Near-Earth Object WISE" (NEOWISE). If the one month post-cryogenic mission proved a success, it would be extended for an additional three months- it was, and the mission continued. The focus of the extended mission was to look for asteroids and comets close to Earth orbit, using the remaining post-cryogenic detection capability. Two of four detectors on WISE work without cryogen. In February 2011, NASA announced that NEOWISE had discovered many new objects in the Solar System, including 20 comets. The spacecraft was put into hibernation on February 1, 2011.

Chapter- 13

Hubble Space Telescope

Hubble Space Telescope



The Hubble Space Telescope as seen from the departing Space Shuttle *Atlantis*, flying Servicing Mission 4 (STS-125), the fifth and final human spaceflight to visit the observatory.

General information

NSSDC ID	1990-037B
Organization	NASA / ESA / STScI
Launch date	April 24, 1990, 8:33:51 am EDT
Launch vehicle	Space Shuttle *Discovery* (STS-31)
Mission length	20 years, 9 months, and 11 days elapsed
Deorbited	due ~2013–2021
Mass	11,110 kg (24,500 lb)

Type of orbit	Near-circular low Earth orbit
Orbit height	559 km (347 mi)
Orbit period	96–97 minutes (14-15 periods per day)
Orbit velocity	7,500 m/s (25,000 ft/s)
Acceleration due to gravity	8.169 m/s^2 (26.80 ft/s^2)
Location	Low Earth orbit
Telescope style	Ritchey-Chrétien reflector
Wavelength	Optical, ultraviolet, near-infrared
Diameter	2.4 m (7 ft 10 in)
Collecting area	4.5 m^2 (48 sq ft)
Focal length	57.6 m (189 ft)
	Instruments
NICMOS	infrared camera/spectrometer
ACS	optical survey camera (partially failed)
WFC3	wide field optical camera
COS	ultraviolet spectrograph
STIS	optical spectrometer/camera
FGS	three fine guidance sensors

The **Hubble Space Telescope** (**HST**) is a space telescope that was carried into orbit by a space shuttle in 1990. Although not the first space telescope, Hubble is one of the largest and most versatile, and is well-known as both a vital research tool and a public relations boon for astronomy. The HST was built by the United States space agency NASA, with contributions from the European Space Agency, and is operated by the Space Telescope Science Institute. It is named after the astronomer Edwin Hubble. The HST is one of NASA's Great Observatories, along with the Compton Gamma Ray Observatory, the Chandra X-ray Observatory, and the Spitzer Space Telescope.

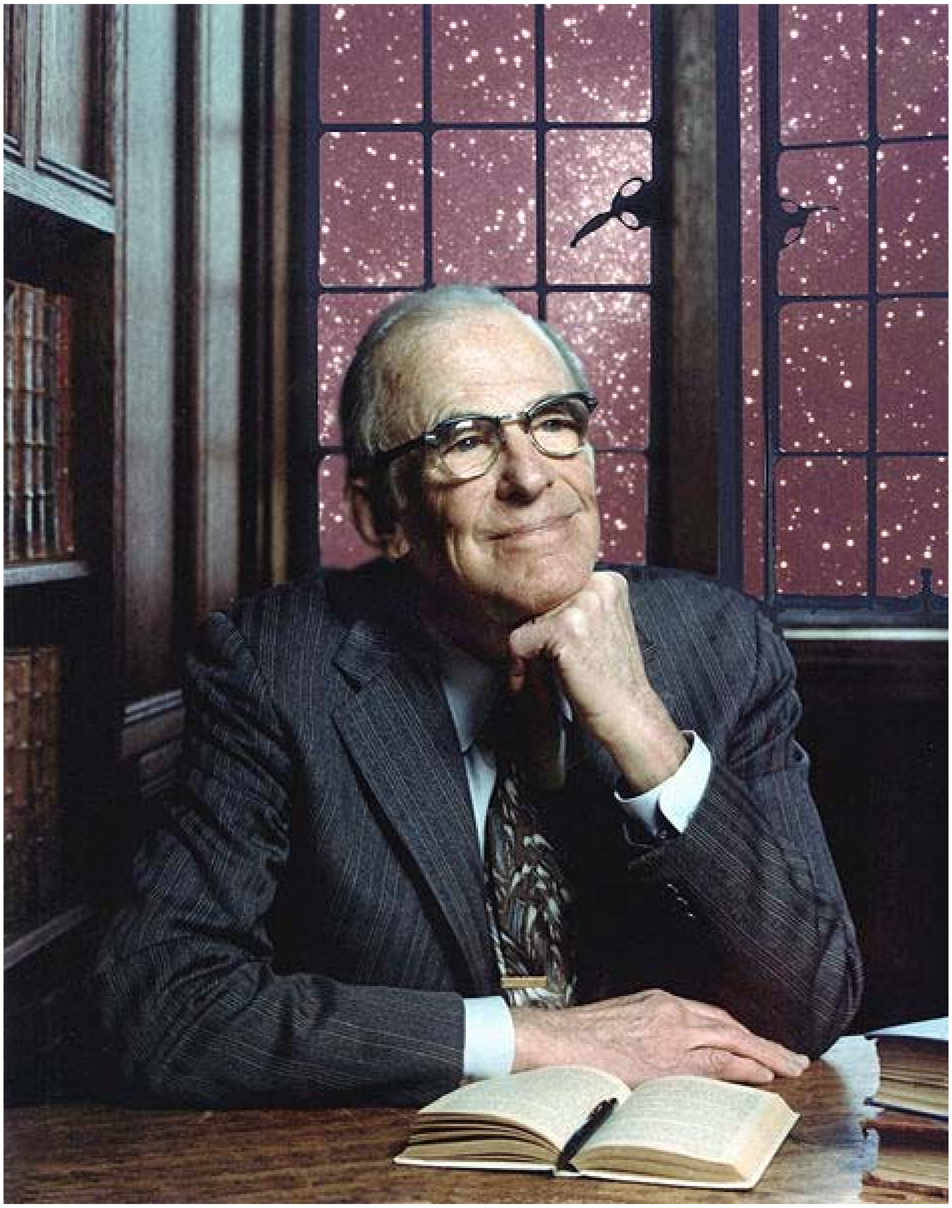
Space telescopes were proposed as early as 1923. Hubble was funded in the 1970s, with a proposed launch in 1983, but the project was beset by technical delays, budget problems, and the *Challenger* disaster. When finally launched in 1990, scientists found that the main mirror had been ground incorrectly, severely compromising the telescope's capabilities. However, after a servicing mission in 1993, the telescope was restored to its intended quality. Hubble's orbit outside the distortion of Earth's atmosphere allows it to take extremely sharp images with almost no background light. Hubble's Ultra Deep Field image, for instance, is the most detailed visible-light image ever made of the universe's most distant objects. Many Hubble observations have led to breakthroughs in astrophysics, such as accurately determining the rate of expansion of the universe.

Hubble is the only telescope designed to be serviced in space by astronauts. Four servicing missions were performed from 1993 to 2002, but the fifth was canceled on safety grounds following the Space Shuttle *Columbia* disaster. However, after spirited public discussion, NASA administrator Mike Griffin approved one final servicing mission, completed in 2009. The telescope is now expected to function until at least 2014, when its scientific successor, the James Webb Space Telescope (JWST), is due to be launched.

Conception, design and aims

Proposals and precursors

In 1923, Hermann Oberth—considered along with Robert H. Goddard and Konstantin Tsiolkovsky fathers of modern rocketry—published *Die Rakete zu den Planetenräumen* ("The Rocket into Planetary Space"), which mentioned how a telescope could be propelled into Earth orbit by a rocket.



Lyman Spitzer, "father" of the Space Telescope

The history of the Hubble Space Telescope can be traced back as far as 1946, when the astronomer Lyman Spitzer wrote the paper "Astronomical advantages of an extraterrestrial observatory". In it, he discussed the two main advantages that a space-based observatory would have over ground-based telescopes. First, the angular resolution (smallest separation at which objects can be clearly distinguished) would be limited only by diffraction, rather than by the turbulence in the atmosphere, which causes stars to twinkle and is known to astronomers as seeing. At that time ground-based telescopes were limited to resolutions of 0.5–1.0 arcseconds, compared to a theoretical diffraction-limited resolution of about 0.05 arcsec for a telescope with a mirror 2.5 m in diameter. Second, a space-based telescope could observe infrared and ultraviolet light, which are strongly absorbed by the atmosphere.

Spitzer devoted much of his career to pushing for a space telescope to be developed. In 1962 a report by the United States National Academy of Sciences recommended the development of a space telescope as part of the space program, and in 1965 Spitzer was appointed as head of a committee given the task of defining the scientific objectives for a large space telescope.

Space-based astronomy had begun on a very small scale following World War II, as scientists made use of developments that had taken place in rocket technology. The first ultraviolet spectrum of the Sun was obtained in 1946, and NASA launched the Orbiting Solar Observatory to obtain UV, X-ray, and gamma-ray spectra in 1962. An orbiting solar telescope was launched in 1962 by the United Kingdom as part of the Ariel space program, and in 1966 National Aeronautics and Space Administration (NASA) launched the first Orbiting Astronomical Observatory (OAO) mission. OAO-1's battery failed after three days, terminating the mission. It was followed by OAO-2, which carried out ultraviolet observations of stars and galaxies from its launch in 1968 until 1972, well beyond its original planned lifetime of one year.

The OSO and OAO missions demonstrated the important role space-based observations could play in astronomy, and 1968 saw the development by NASA of firm plans for a space-based reflecting telescope with a mirror 3 m in diameter, known provisionally as the Large Orbiting Telescope or Large Space Telescope (LST), with a launch slated for 1979. These plans emphasized the need for manned maintenance missions to the telescope to ensure such a costly program had a lengthy working life, and the concurrent development of plans for the reusable space shuttle indicated that the technology to allow this was soon to become available.

Quest for funding

The continuing success of the OAO program encouraged increasingly strong consensus within the astronomical community that the LST should be a major goal. In 1970 NASA established two committees, one to plan the engineering side of the space telescope project, and the other to determine the scientific goals of the mission. Once these had been established, the next hurdle for NASA was to obtain funding for the instrument, which would be far more costly than any Earth-based telescope. The US Congress questioned many aspects of the proposed budget for the telescope and forced cuts in the budget for the planning stages, which at the time consisted of very detailed studies of potential instruments and hardware for the telescope. In 1974, public spending cuts instigated by Gerald Ford led to Congress cutting all funding for the telescope project.

In response to this, a nationwide lobbying effort was coordinated among astronomers. Many astronomers met congressmen and senators in person, and large scale letter-writing campaigns were organized. The National Academy of Sciences published a report emphasizing the need for a space telescope, and eventually the Senate agreed to half of the budget that had originally been approved by Congress.

The funding issues led to something of a reduction in the scale of the project, with the proposed mirror diameter reduced from 3 m to 2.4 m, both to cut costs and to allow a more compact and effective configuration for the telescope hardware. A proposed precursor 1.5 m space telescope to test the systems to be used on the main satellite was dropped, and budgetary concerns also prompted collaboration with the European Space Agency. ESA agreed to provide funding and supply one of the first generation instruments for the telescope, as well as the solar cells that would power it, and staff to work on the telescope in the United States, in return for European astronomers being guaranteed at least 15% of the observing time on the telescope. Congress eventually approved funding of US$36,000,000 for 1978, and the design of the LST began in earnest, aiming for a launch date of 1983. In 1983 the telescope was named after Edwin Hubble, who made one of the greatest scientific breakthroughs of the 20th century when he discovered that the universe is expanding.

Construction and engineering

Polishing of Hubble's primary mirror begins at Perkin-Elmer corporation, Danbury, Connecticut, March 1979. The engineer pictured is Dr. Martin Yellin, an optical engineer working for Perkin-Elmer on the project.

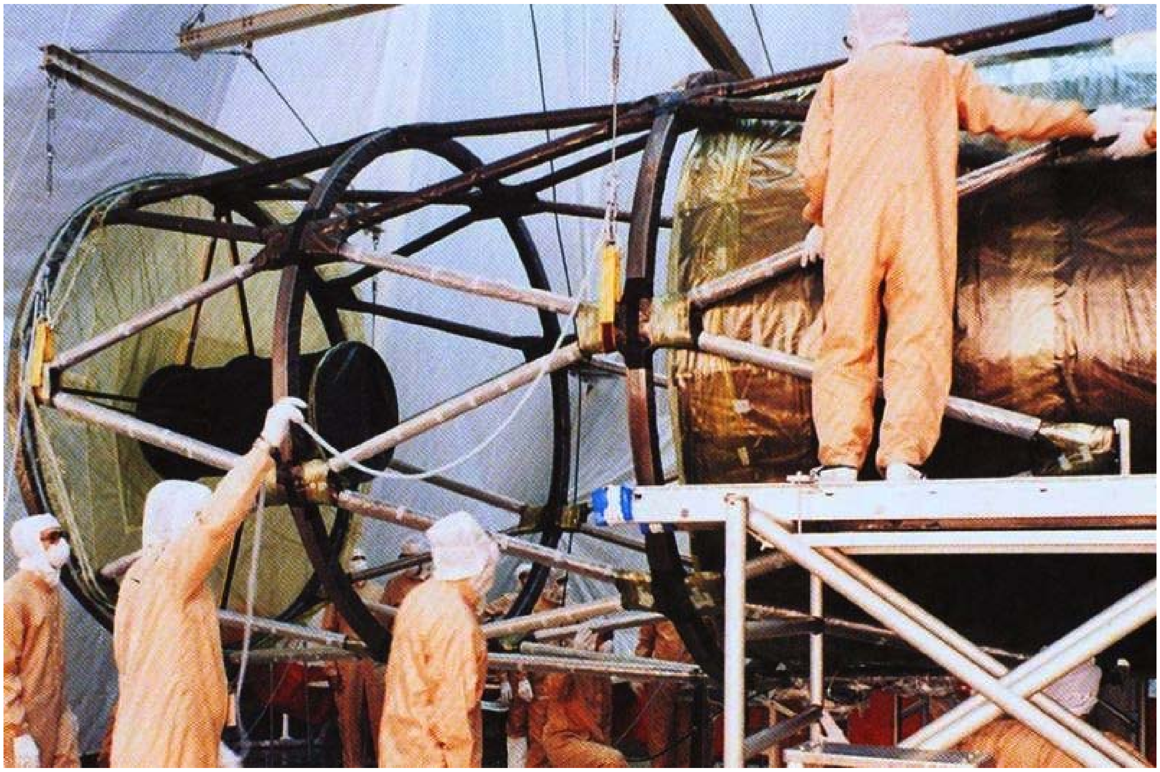
Once the Space Telescope project had been given the go-ahead, work on the program was divided among many institutions. Marshall Space Flight Center (MSFC) was given responsibility for the design, development, and construction of the telescope, while the Goddard Space Flight Center was given overall control of the scientific instruments and ground-control center for the mission. MSFC commissioned the optics company Perkin-Elmer to design and build the Optical Telescope Assembly (OTA) and Fine Guidance Sensors for the space telescope. Lockheed was commissioned to construct and integrate the spacecraft in which the telescope would be housed.

Optical Telescope Assembly (OTA)

Optically, the HST is a Cassegrain reflector of Ritchey-Chrétien design, as are most large professional telescopes. This design, with two hyperbolic mirrors, is known for good imaging performance over a wide field of view, with the disadvantage that the mirrors have shapes that are hard to fabricate and test. The mirror and optical systems of the telescope determine the final performance, and they were designed to exacting specifications. Optical telescopes typically have mirrors polished to an accuracy of about a tenth of the wavelength of visible light, but the Space Telescope was to be used for observations from the visible through the ultraviolet (shorter wavelengths) and was specified to be diffraction limited to take full advantage of the space environment. Therefore its mirror needed to be polished to an accuracy of 10 nanometres, or about 1/65 of the wavelength of red light. On the long wavelength end, the OTA was not designed with optimum IR performance in mind — for example, the mirrors are kept at stable (and warm, about 15 °C) temperatures by heaters. This limits Hubble's performance as an infrared telescope.

Perkin-Elmer intended to use custom-built and extremely sophisticated computer-controlled polishing machines to grind the mirror to the required shape. However, in case their cutting-edge technology ran into difficulties, NASA demanded that PE sub-contract to Kodak to construct a back-up mirror using traditional mirror-polishing techniques. (The team of Kodak and Itek also bid on the original mirror polishing work. Their bid called for the two companies to double-check each other's work, which would have almost certainly caught the polishing error that later caused such problems.) The Kodak mirror is now on permanent display at the Smithsonian Institution. An Itek mirror built as part of the effort is now used in the 2.4 m telescope at the Magdalena Ridge Observatory.

Construction of the Perkin-Elmer mirror began in 1979, starting with a blank manufactured by Corning from their ultra-low expansion glass. To keep the mirror's weight to a minimum it consisted of inch-thick top and bottom plates sandwiching a honeycomb lattice. Perkin-Elmer simulated microgravity by supporting the mirror on both sides with 138 rods that exerted varying amounts of force. This ensured that the mirror's final shape would be correct and to specification when finally deployed. Mirror polishing continued until May 1981. NASA reports at the time questioned Perkin-Elmer's managerial structure, and the polishing began to slip behind schedule and over budget. To save money, NASA halted work on the back-up mirror and put the launch date of the telescope back to October 1984. The mirror was completed by the end of 1981; it was washed using 2,400 gallons (9,100 L) of hot, deionized water and then received a reflective coating of aluminium 65 nm-thick and a protective coating of magnesium fluoride 25 nm-thick.

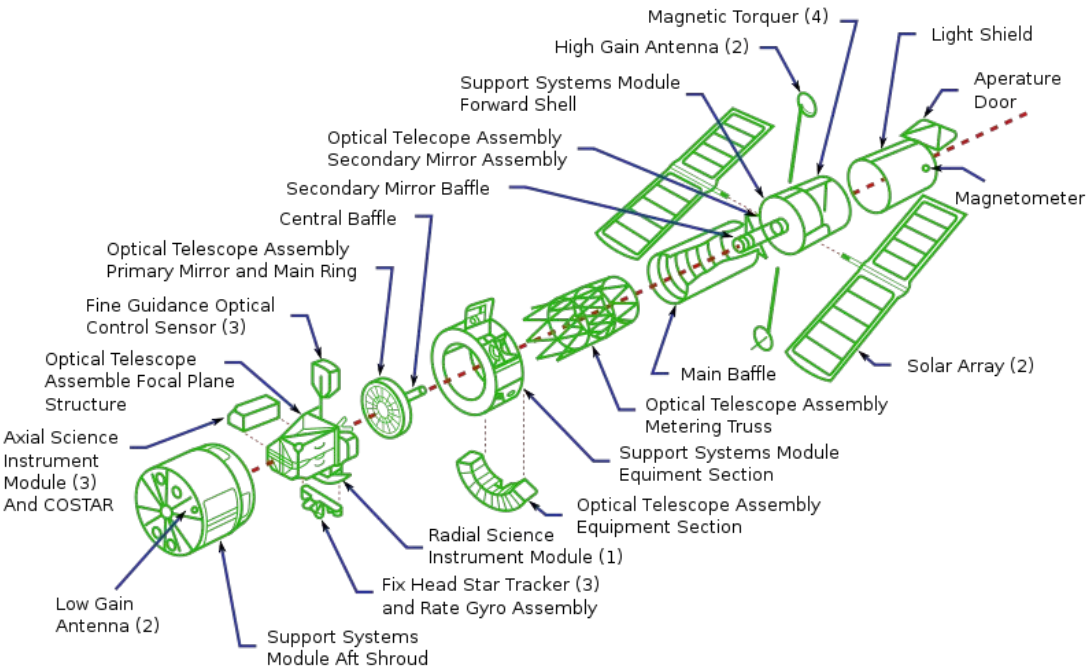


Construction of Hubble. The optical metering truss and secondary baffle are visible.

Doubts continued to be expressed about Perkin-Elmer's competence on a project of this importance, as their budget and timescale for producing the rest of the OTA continued to inflate. In response to a schedule described as "unsettled and changing daily", NASA postponed the launch date of the telescope until April 1985. Perkin-Elmer's schedules continued to slip at a rate of about one month per quarter, and at times delays reached one day for each day of work. NASA was forced to postpone the launch date until first March and then September 1986. By this time the total project budget had risen to US$1.175 billion.

Spacecraft systems

The spacecraft in which the telescope and instruments were to be housed was another major engineering challenge. It would have to adequately withstand frequent passages from direct sunlight into the darkness of Earth's shadow, which would generate major changes in temperature, while being stable enough to allow extremely accurate pointing of the telescope. A shroud of multi-layer insulation keeps the temperature within the telescope stable, and surrounds a light aluminum shell in which the telescope and instruments sit. Within the shell, a graphite-epoxy frame keeps the working parts of the telescope firmly aligned. Because graphite composites are hygroscopic, there was a risk that water vapor absorbed by the truss while in Lockheed's clean room would later be expressed in the vacuum of space; the telescope's instruments would be covered in ice. To reduce that risk, a nitrogen gas purge was performed prior to launching the telescope into space.



Exploded view of the Hubble Telescope.

While construction of the spacecraft in which the telescope and instruments would be housed proceeded somewhat more smoothly than the construction of the OTA, Lockheed still experienced some budget and schedule slippage, and by the summer of 1985, construction of the spacecraft was 30% over budget and three months behind schedule. An MSFC report said that Lockheed tended to rely on NASA directions rather than take their own initiative in the construction.

Initial instruments

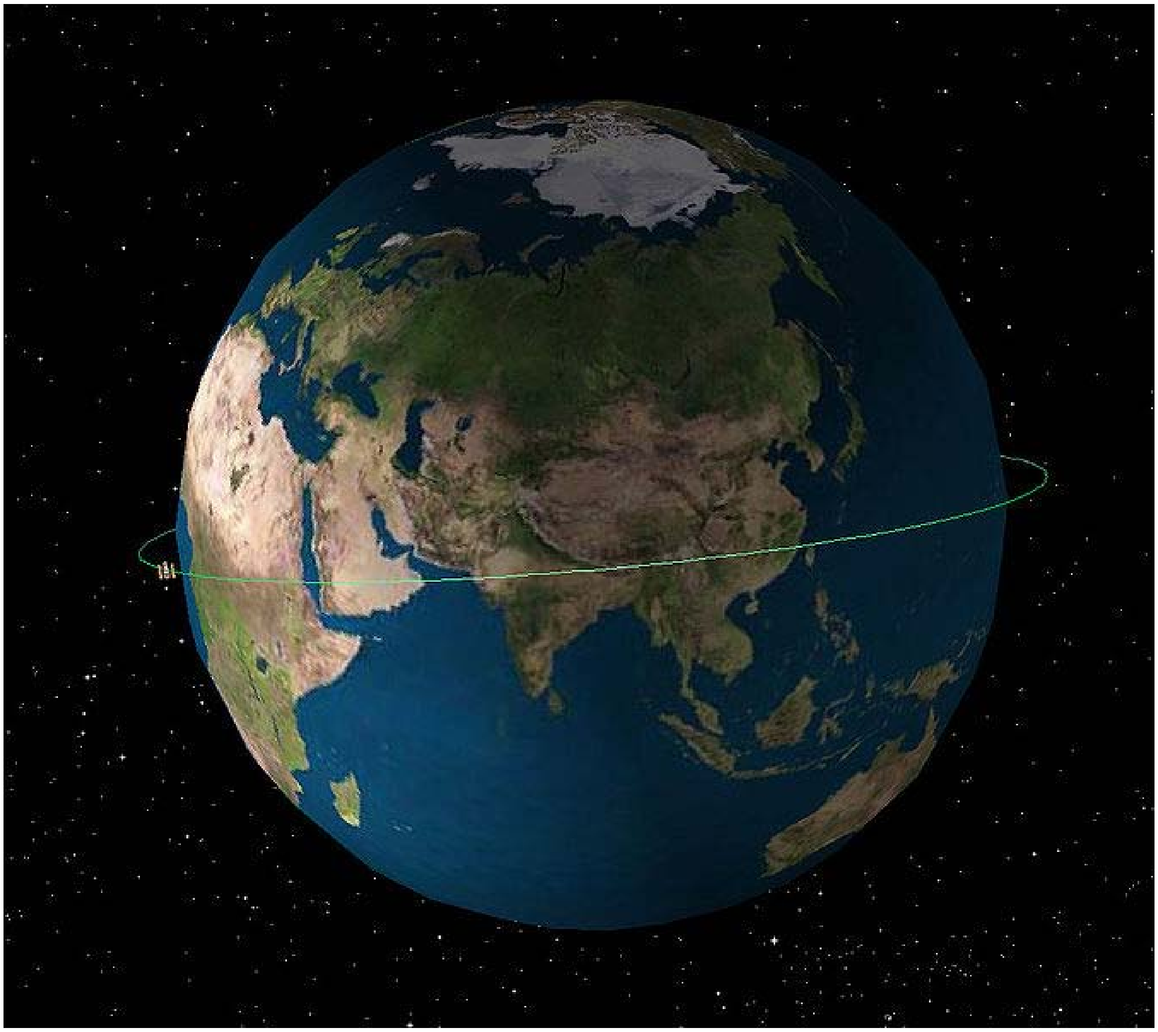
When launched, the HST carried five scientific instruments: the Wide Field and Planetary Camera (WF/PC), Goddard High Resolution Spectrograph (GHRS), High Speed Photometer (HSP), Faint Object Camera (FOC) and the Faint Object Spectrograph (FOS). WF/PC was a high-resolution imaging device primarily intended for optical observations. It was built by NASA's Jet Propulsion Laboratory, and incorporated a set of 48 filters isolating spectral lines of particular astrophysical interest. The instrument contained eight charge-coupled device (CCD) chips divided between two cameras, each using four CCDs. The "wide field camera" (WFC) covered a large angular field at the expense of resolution, while the "planetary camera" (PC) took images at a longer effective focal length than the WF chips, giving it a greater magnification.

The GHRS was a spectrograph designed to operate in the ultraviolet. It was built by the Goddard Space Flight Center and could achieve a spectral resolution of 90,000. Also optimized for ultraviolet observations were the FOC and FOS, which were capable of the highest spatial resolution of any instruments on Hubble. Rather than CCDs these three instruments used photon-counting digicons as their detectors. The FOC was constructed by ESA, while the University of California, San Diego and the Martin Marietta corporation built the FOS.

The final instrument was the HSP, designed and built at the University of Wisconsin–Madison. It was optimized for visible and ultraviolet light observations of variable stars and other astronomical objects varying in brightness. It could take up to 100,000 measurements per second with a photometric accuracy of about 2% or better.

HST's guidance system can also be used as a scientific instrument. Its three Fine Guidance Sensors (FGS) are primarily used to keep the telescope accurately pointed during an observation, but can also be used to carry out extremely accurate astrometry; measurements accurate to within 0.0003 arcseconds have been achieved.

Ground support



Hubble's low orbit means many targets are visible for somewhat less than half of elapsed time, since they are blocked from view by the Earth for one-half of each orbit.

The Space Telescope Science Institute (STScI) is responsible for the scientific operation of the telescope and delivery of data products to astronomers. STScI is operated by the Association of Universities for Research in Astronomy (AURA) and is physically located in Baltimore, Maryland on the Homewood campus of Johns Hopkins University, one of the 33 US universities and 7 international affiliates that make up the AURA consortium. STScI was established in 1981 after something of a power struggle between NASA and the scientific community at large. NASA had wanted to keep this function "in-house", but scientists wanted it to be based in an academic establishment. The Space Telescope European Coordinating Facility (ST-ECF), established at Garching bei München near Munich in 1984, provides similar support for European astronomers.

One rather complex task that falls to STScI is scheduling observations for the telescope. Hubble is situated in a low-Earth orbit so that it can be reached by the space shuttle for servicing missions, but this means that most astronomical targets are occulted by the Earth for slightly less than half of each orbit. Observations cannot take place when the telescope passes through the South Atlantic Anomaly due to elevated radiation levels, and there are also sizable exclusion zones around the Sun (precluding observations of Mercury), Moon and Earth. The solar avoidance angle is about 50°, which is specified to keep sunlight from illuminating any part of the OTA. Earth and Moon avoidance is to keep bright light out of the FGSs and to keep scattered light from entering the instruments. If the FGSs are turned off, however, the Moon and Earth can be observed. Earth observations were used very early in the program to generate flat-fields for the WFPC1 instrument. There is a so-called continuous viewing zone (CVZ), at roughly 90 degrees to the plane of Hubble's orbit, in which targets are not occulted for long periods. Due to the precession of the orbit, the location of the CVZ moves slowly over a period of eight weeks. Because the limb of the Earth is always within about 30° of regions within the CVZ, the brightness of scattered earthshine may be elevated for long periods during CVZ observations.

Because Hubble orbits in the upper atmosphere, its orbit changes over time in a way that is not accurately predictable. The density of the upper atmosphere varies according to many factors, and this means that Hubble's predicted position for six weeks' time could be in error by up to 4,000 km. Observation schedules are typically finalized only a few days in advance, as a longer lead time would mean there was a chance that the target would be unobservable by the time it was due to be observed.

Engineering support for HST is provided by NASA and contractor personnel at the Goddard Space Flight Center in Greenbelt, Maryland, 48 km south of the STScI. Hubble's operation is monitored 24 hours per day by four teams of flight controllers who make up Hubble's Flight Operations Team.

Challenger disaster, delays, and eventual launch

By early 1986, the planned launch date of October that year looked feasible, but the Challenger accident brought the U.S. space program to a halt, grounding the space shuttle fleet and forcing the launch of Hubble to be postponed for several years. The telescope had to be kept in a clean room, powered up and purged with nitrogen, until a launch could be rescheduled. This costly situation (about $6 million per month) pushed the overall costs of the project even higher. On the other hand, engineers used this time to perform extensive tests, swap out a possibly failure-prone battery, and make other improvements. Furthermore, the ground software needed to control Hubble was not ready in 1986, and in fact was barely ready by the 1990 launch.

Shuttle mission STS-31 lifts off, carrying Hubble into orbit.

Eventually, following the resumption of shuttle flights in 1988, the launch of the telescope was scheduled for 1990. On April 24, 1990, shuttle mission STS-31 saw *Discovery* launch the telescope successfully into its planned orbit.

From its original total cost estimate of about US$400 million, the telescope had by now cost over $2.5 billion to construct. Hubble's cumulative costs up to this day are estimated to be several times higher still, with US expenditure estimated at between $4.5 and $6 billion, and Europe's financial contribution at €593 million (1999 estimate).

Flawed mirror

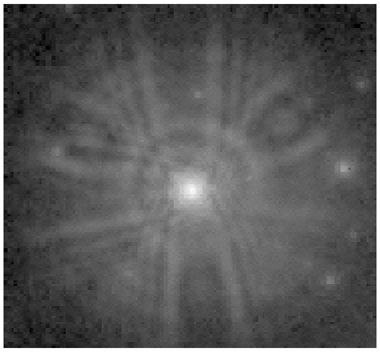
Within weeks of the launch of the telescope, the returned images showed that there was a serious problem with the optical system. Although the first images appeared to be sharper than ground-based images, the telescope failed to achieve a final sharp focus, and the best image quality obtained was drastically lower than expected. Images of point sources spread out over a radius of more than one arcsecond, instead of having a point spread function (PSF) concentrated within a circle 0.1 arcsec in diameter as had been specified in the design criteria. The detailed performance is shown in graphs from STScI illustrating the mis-figured PSFs compared to post-correction and ground-based PSFs.

Analysis of the flawed images showed that the cause of the problem was that the primary mirror had been ground to the wrong shape. Although it was probably the most precisely figured mirror ever made, with variations from the prescribed curve of only 10 nanometers, it was too flat at the edges by about 2200 nanometers (2.2 microns). This difference was catastrophic, introducing severe spherical aberration, a flaw in which light reflecting off the edge of a mirror focuses on a different point from the light reflecting off its center.

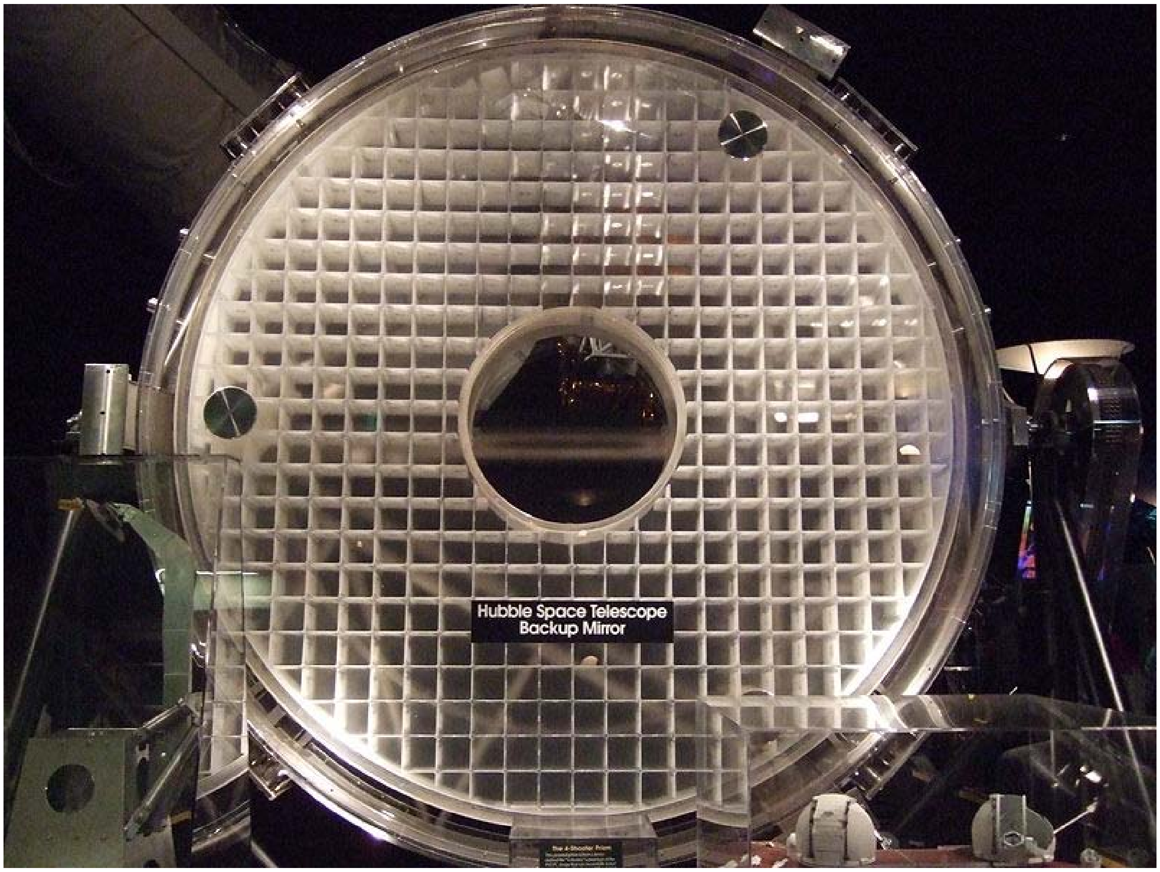
Hubble is deployed from *Discovery*.

The effect of the mirror flaw on scientific observations depended on the particular observation—the core of the aberrated PSF was sharp enough to permit high-resolution observations of bright objects, and spectroscopy was largely unaffected. However, the loss of light to the large, out of focus halo severely reduced the usefulness of the telescope for faint objects or high contrast imaging. This meant that nearly all of the cosmological programs were essentially impossible, since they required observation of exceptionally faint objects. NASA and the telescope became the butt of many jokes, and the project was popularly regarded as a white elephant. (For instance, in the 1991 comedy *The Naked Gun 2½: The Smell of Fear*, the Hubble was pictured with the *Titanic*, the *Hindenburg*, and the Edsel). Nonetheless, during the first three years of the Hubble mission, before the optical corrections, the telescope still carried out a large number of productive observations. The error was well characterized and stable, enabling astronomers to optimize the results obtained using sophisticated image processing techniques such as deconvolution.

Origin of the problem



An extract from a WF/PC image shows the light from a star spread over a wide area instead of being concentrated on a few pixels.

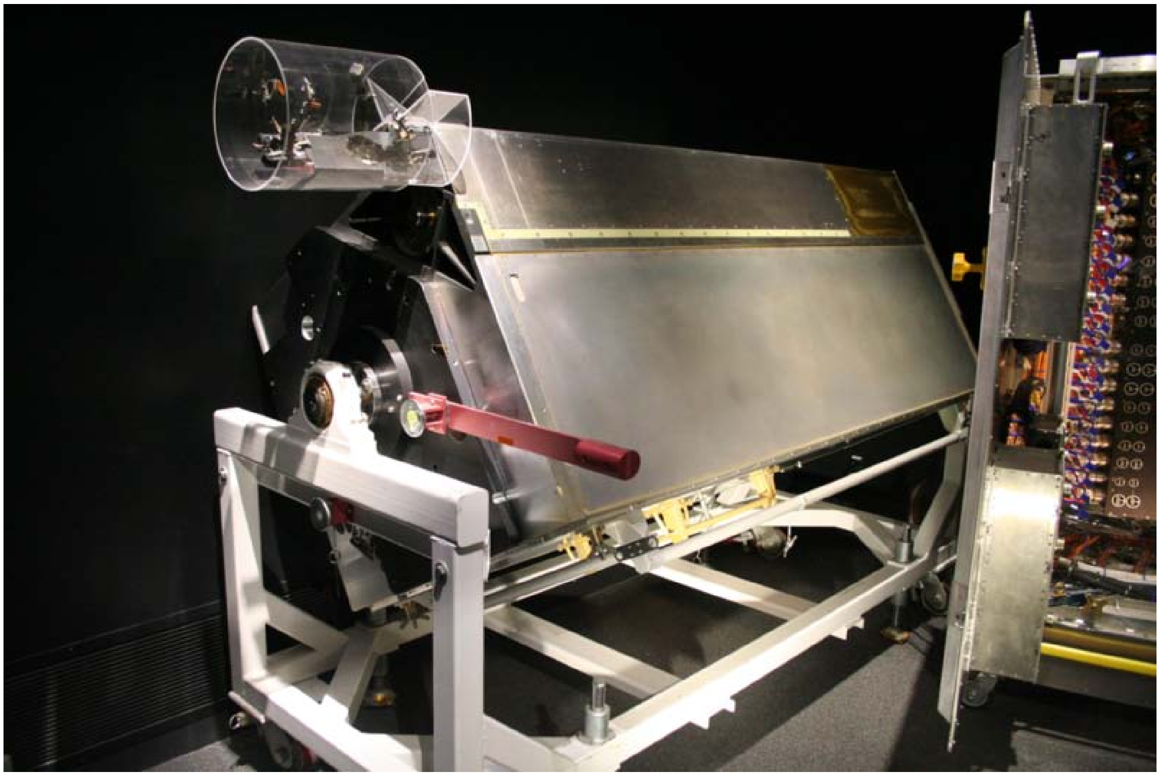


The correctly ground backup mirror built by Eastman Kodak for the Hubble space telescope (the mirror was never coated with a reflective surface, hence its inner support structure can be seen). It now resides in the National Air and Space Museum in Washington, DC.

A commission headed by Lew Allen, director of the Jet Propulsion Laboratory, was established to determine how the error could have arisen. The Allen Commission found that the main null corrector, a device used to measure the exact shape of the mirror, had been incorrectly assembled—one lens was wrongly spaced by 1.3 mm. During the polishing of the mirror, Perkin-Elmer had analyzed its surface with two other null correctors, both of which correctly indicated that the mirror was suffering from spherical aberration. The company ignored these test results, as it believed that the two null correctors were less accurate than the primary device that was reporting that the mirror was perfectly figured.

The commission blamed the failings primarily on Perkin-Elmer. Relations between NASA and the optics company had been severely strained during the telescope construction, due to frequent schedule slippage and cost overruns. NASA found that Perkin-Elmer did not review or supervise the mirror construction adequately, did not assign its best optical scientists to the project (as it had for the prototype), and in particular did not involve the optical designers in the construction and verification of the mirror. While the commission heavily criticized Perkin-Elmer for these managerial failings, NASA was also criticized for not picking up on the quality control shortcomings, such as relying totally on test results from a single instrument.

Design of a solution



COSTAR on display at the National Air and Space Museum

The design of the telescope had always incorporated servicing missions, and astronomers immediately began to seek potential solutions to the problem that could be applied at the first servicing mission, scheduled for 1993. While Kodak and Itek had each ground back-up mirrors for Hubble, it would have been impossible to replace the mirror in orbit, and too expensive and time-consuming to bring the telescope temporarily back to Earth for a refit. Instead, the fact that the mirror had been ground so precisely to the wrong shape led to the design of new optical components with exactly the same error but in the opposite sense, to be added to the telescope at the servicing mission, effectively acting as "spectacles" to correct the spherical aberration.

The first step was a precise characterization of the error in the main mirror. Working backwards from images of point sources, astronomers determined that the conic constant of the mirror as built was −1.01390±0.0002, instead of the intended −1.00230. The same number was also derived by analyzing the null corrector used by Perkin-Elmer to figure the mirror, as well as by analyzing interferograms obtained during ground testing of the mirror.

Because of the way the HST's instruments were designed, two different sets of correctors were required. The design of the Wide Field and Planetary Camera 2, already planned to replace the existing WF/PC, included relay mirrors to direct light onto the eight separate CCD chips making up its two cameras. An inverse error built into their surfaces could completely cancel the aberration of the primary. However, the other instruments lacked any intermediate surfaces that could be figured in this way, and so required an external correction device.

The Corrective Optics Space Telescope Axial Replacement (COSTAR) system was designed to correct the spherical aberration for light focused at the FOC, FOS, and GHRS. It consists of two mirrors in the light path with one ground to correct the aberration. To fit the COSTAR system onto the telescope, one of the other instruments had to be removed, and astronomers selected the High Speed Photometer to be sacrificed. By 2002 all of the original instruments requiring COSTAR had been replaced by instruments with their own corrective optics. COSTAR was removed and returned to Earth in 2009 where it is exhibited at the National Air and Space Museum. The area previously used by COSTAR is now occupied by the Cosmic Origins Spectrograph.

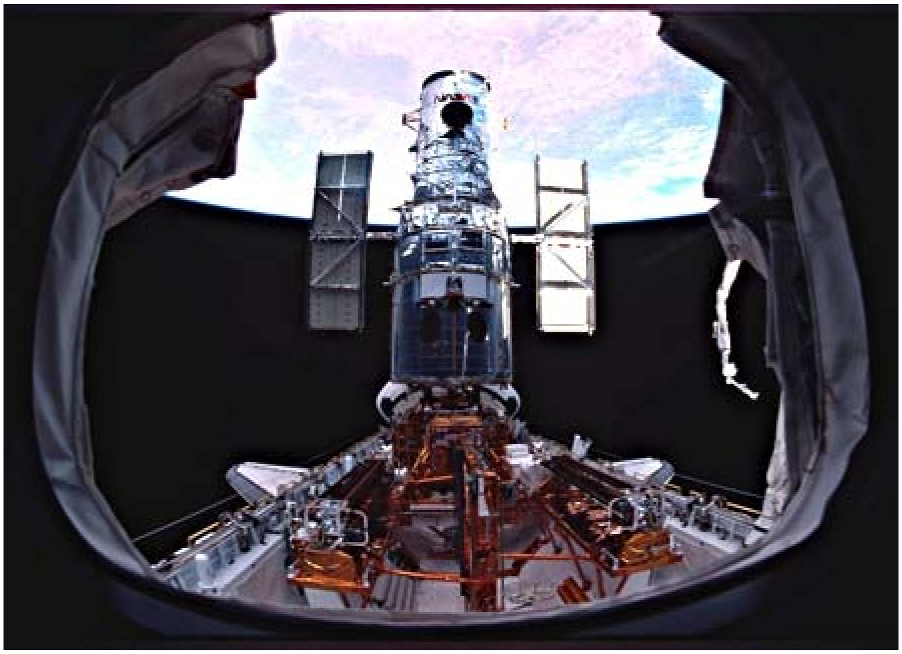
Servicing missions and new instruments

Servicing Mission 1

Astronauts installing corrective optics during SM1

Improvement in Hubble images after SM1

Astronauts replacing gyroscopes during SM3A



Hubble on the payload bay just prior to release during SM3B

The telescope had always been designed so that it could be regularly serviced, but after the problems with the mirror came to light, the first servicing mission assumed a much greater importance, as the astronauts would have to carry out extensive work on the telescope to install the corrective optics. The seven astronauts selected for the mission were trained intensively in the use of the hundred or more specialized tools that would be needed. The Space Shuttle *Endeavour* mission STS-61 took place in December 1993, and involved installation of several instruments and other equipment over a total of 10 days.

Most importantly, the High Speed Photometer was replaced with the COSTAR corrective optics package, and WFPC was replaced with the Wide Field and Planetary Camera 2 (WFPC2) with its internal optical correction system. In addition, the solar arrays and their drive electronics were replaced, as well as four of the gyroscopes used in the telescope pointing system, two electrical control units and other electrical components, and two magnetometers. The onboard computers were upgraded, and finally, the telescope's orbit was boosted, to compensate for the orbital decay from 3 years of drag in the tenuous upper atmosphere.

On January 13, 1994, NASA declared the mission a complete success and showed the first of many much sharper images. At the time, the mission had been one of the most complex ever undertaken, involving five lengthy periods of extra-vehicular activity, and its resounding success was an enormous boon for NASA, as well as for the astronomers who now had a fully capable space telescope.

Servicing Mission 2

Servicing Mission 2, flown by *Discovery* (STS-82) in February 1997, replaced the GHRS and the FOS with the Space Telescope Imaging Spectrograph (STIS) and the Near Infrared Camera and Multi-Object Spectrometer (NICMOS), replaced an Engineering and Science Tape Recorder with a new Solid State Recorder, repaired thermal insulation and again boosted Hubble's orbit. NICMOS contained a heat sink of solid nitrogen to reduce the thermal noise from the instrument, but shortly after it was installed, an unexpected thermal expansion resulted in part of the heat sink coming into contact with an optical baffle. This led to an increased warming rate for the instrument and reduced its original expected lifetime of 4.5 years to about 2 years.

Servicing Mission 3A

Servicing Mission 3A flown by *Discovery* (STS-103), took place in December 1999, and was a split-off from Servicing Mission 3 after three of the six onboard gyroscopes had failed. (A fourth failed a few weeks before the mission, rendering the telescope incapable of performing science observations.) The mission replaced all six gyroscopes, replaced a Fine Guidance Sensor and the computer, installed a Voltage/temperature Improvement Kit (VIK) to prevent battery overcharging, and replaced thermal insulation blankets. Although the new computer is hardly a powerhouse (a 25 MHz radiation hardened Intel 486 with two megabytes of RAM), it is still 20 times faster, with six times more memory, than the DF-224 it replaced. The new computer increases throughput by moving some computing tasks from the ground to the spacecraft, and saves money by allowing the use of modern programming languages.

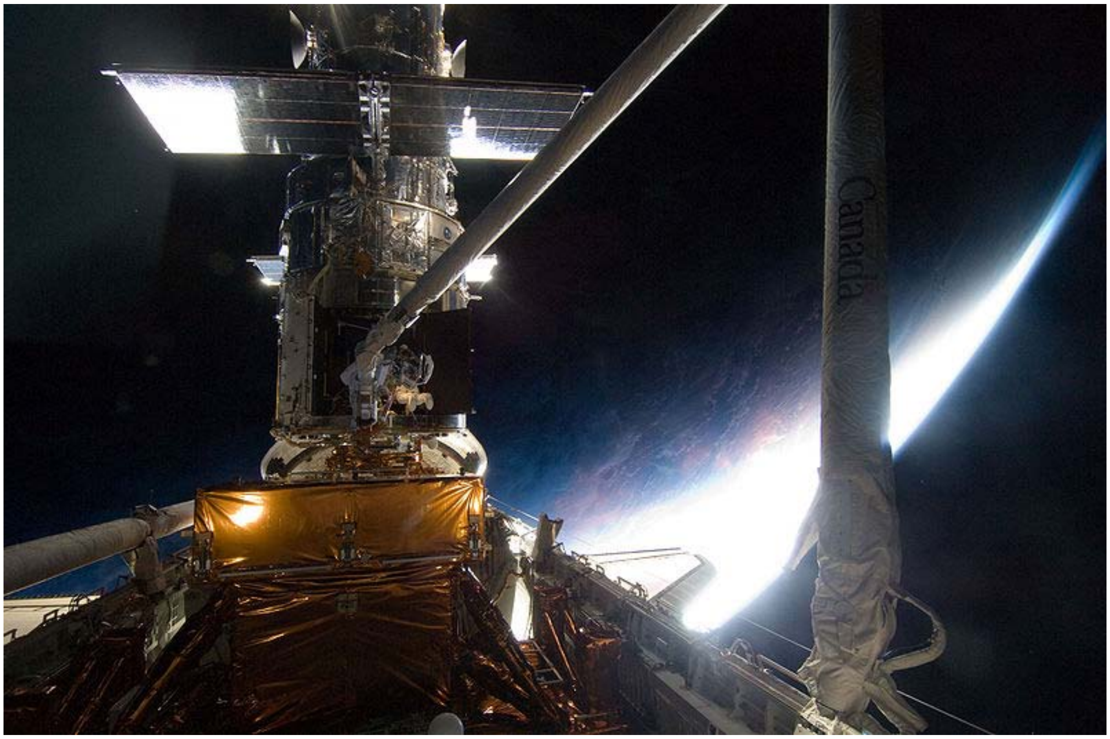
Servicing Mission 3B

Servicing Mission 3B flown by *Columbia* (STS-109) in March 2002 saw the installation of a new instrument, with the FOC (the last original instrument) being replaced by the Advanced Camera for Surveys (ACS). This meant that COSTAR was no longer required, since all new instruments had correction for the main mirror aberration built in.

The mission also saw the revival of NICMOS, which had run out of coolant in 1999. A new cooling system was installed that reduced the instrument's temperature enough for it to be usable again. Although not as cold as its original design called for, the temperature is more stable, in many ways a better tradeoff. ACS in particular enhanced Hubble's capabilities; it and the revived NICMOS together imaged the Hubble Ultra Deep Field.

The mission replaced the solar arrays for the second time. The new arrays were derived from those built for the Iridium comsat system and were only two-thirds the size of the old arrays, resulting in less drag against the tenuous reaches of the upper atmosphere while providing 30 percent more power. The additional power allowed all instruments on board the HST to be run simultaneously, and reduced a vibration problem that occurred when the old, less rigid arrays entered and left direct sunlight. Hubble's Power Distribution Unit was also replaced in order to correct a problem with sticky relays, a procedure that required the complete electrical power down of the spacecraft for the first time since it was launched.

Servicing Mission 4



Astronauts work on Hubble during SM4

Hubble floats free from *Atlantis* after SM4.

Servicing Mission 4 (SM4), which took place in May 2009, was the last scheduled shuttle mission (STS-125) for the Hubble Space Telescope. The mission was first planned for October 14, 2008. However on September 27, 2008, the Science Instrument Command and Data Handling (SI C&DH) unit on HST failed. All science data pass through this unit before they can be transmitted to Earth. Although it had a backup unit, if the backup were to fail, the HST's useful life would be over. Therefore on September 29, 2008, NASA announced that the launch of SM4 would be postponed until 2009 so the SI C&DH unit could be replaced as well. SM4, with a replacement SI C&DH unit, was launched aboard Space Shuttle *Atlantis* on May 11, 2009.

On SM4, astronauts, over the course of five spacewalks, installed two new instruments, Wide Field Camera 3 (WFC3), and the Cosmic Origins Spectrograph (COS). WFC3 will increase Hubble's observational capabilities in the ultraviolet and visible spectral ranges by up to 35 times due to its higher sensitivity and wider field of view. The telephone-booth sized COS assembly replaced the Corrective Optics Space Telescope Axial Replacement (COSTAR) that was installed in 1993 to correct Hubble's spherical aberration problems. (COSTAR was no longer needed after the replacement of the FOC in 2002, the last original instrument without the necessary correction built in.) The COS will do observations in the ultraviolet parts of the spectrum, complementing the measurements done by the repaired STIS system.

The mission repaired two instruments that had failed, the Advanced Camera for Surveys (ACS) and the Space Telescope Imaging Spectrograph (STIS). The astronauts also performed other component replacements, including all three Rate Sensor Units (each containing two gas-bearing gyroscopes); one of three Fine Guidance Sensor (FGS) units used to help keep pointing accuracy and increase platform stability; the SI C&DH unit; all six of the 125-pound (57 kg) nickel-hydrogen batteries used to provide all Hubble's electrical power to support operations during the night portion of its orbit; and three New Outer Blanket Layer (NOBL) thermal insulation protective blankets. The batteries had never been replaced and were more than 13 years over their original design life.

Atlantis released the Hubble Space Telescope on May 19, 2009 back into space after all repairs were successfully made. After testing and calibration, Hubble resumed routine operation in September 2009. These efforts are expected to keep the telescope fully functioning at least into 2014, and perhaps longer.

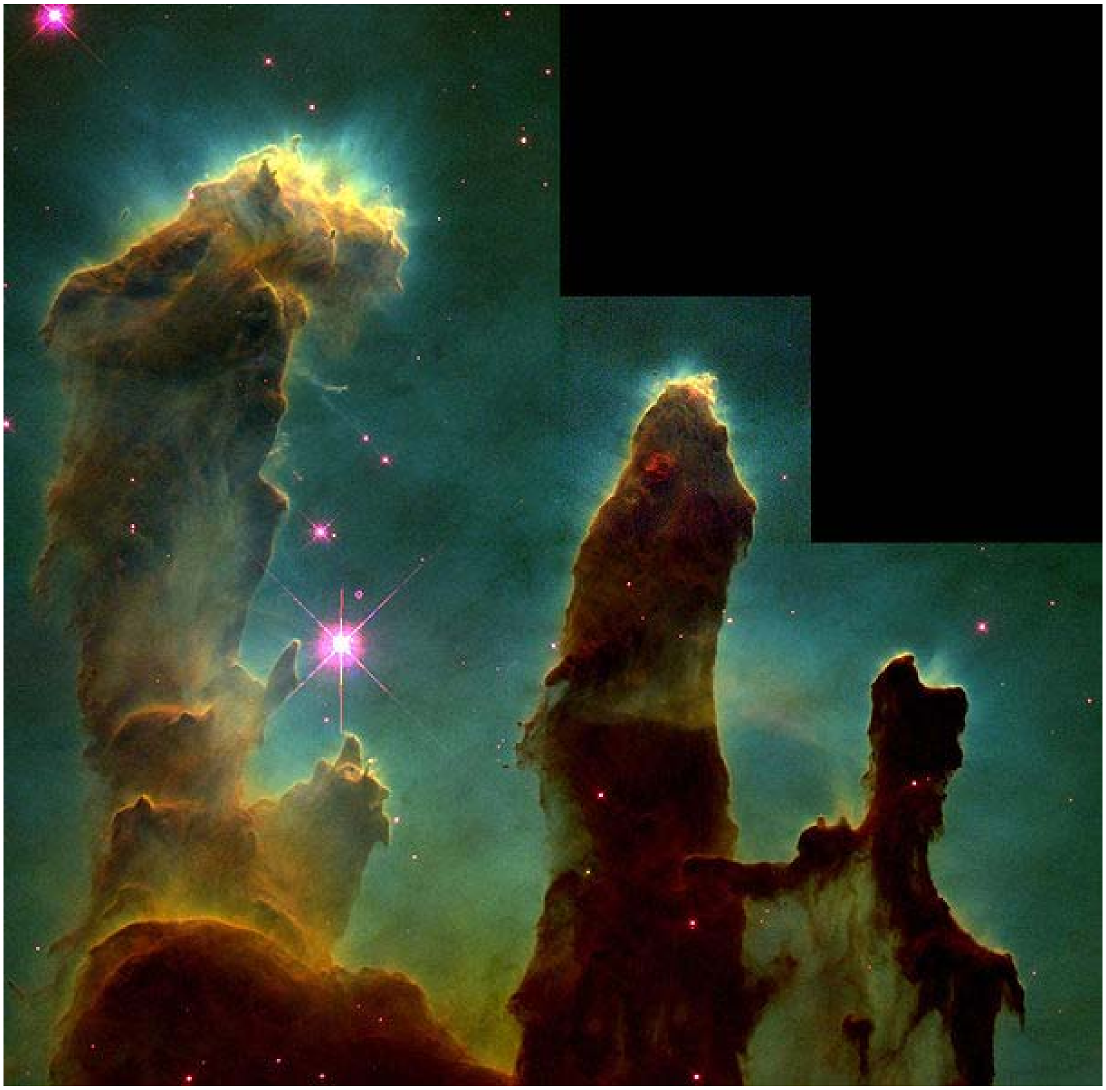
Hubble was originally designed to be returned to earth on board a shuttle. With the retirement of the shuttle fleet, projected for 2011, this will no longer be possible. NASA engineers developed the Soft Capture and Rendezvous System (SCRS), a ring-like device that was attached to Hubble’s aft bulkhead during SM4, which will enable the future rendezvous, capture, and safe disposal of Hubble by either a crewed or robotic mission. The next mission will be to deorbit Hubble at the end of its service life.

Scientific results

Key Projects

In the early 1980s, NASA and StScI convened four panels to discuss Key Projects. These were projects that were both scientifically important and would require significant telescope time, which would be explicitly dedicated to each project. This guaranteed that these particular projects would be completed early, in case the telescope failed sooner than expected. The panels identified three such projects: (1) a study of the nearby intergalactic medium using quasar absorption lines to determine the properties of the intergalactic medium and the gaseous content of galaxies and groups of galaxies; (2) a medium deep survey using the Wide Field Camera to take data whenever one of the other instruments was being used and (3) a project to determine the Hubble Constant within ten percent by reducing the errors, both external and internal, in the calibration of the distance scale.

Important discoveries



One of Hubble's most famous images, *Pillars of Creation* shows stars forming in the Eagle Nebula

Hubble has helped to resolve some long-standing problems in astronomy, as well as turning up results that have required new theories to explain them. Among its primary mission targets was to measure distances to Cepheid variable stars more accurately than ever before, and thus constrain the value of the Hubble constant, the measure of the rate at which the universe is expanding, which is also related to its age. Before the launch of HST, estimates of the Hubble constant typically had errors of up to 50%, but Hubble measurements of Cepheid variables in the Virgo Cluster and other distant galaxy clusters provided a measured value with an accuracy of ±10%, which is consistent with other more accurate measurements made since Hubble's launch using other techniques.

While Hubble helped to refine estimates of the age of the universe, it also cast doubt on theories about its future. Astronomers from the High-z Supernova Search Team and the Supernova Cosmology Project used the telescope to observe distant supernovae and uncovered evidence that, far from decelerating under the influence of gravity, the expansion of the universe may in fact be accelerating. This acceleration was later measured more accurately by other ground-based and space-based telescopes, confirming Hubble's finding. The cause of this acceleration remains poorly understood; the most common cause attributed is dark energy.

The high-resolution spectra and images provided by the HST have been especially well-suited to establishing the prevalence of black holes in the nuclei of nearby galaxies. While it had been hypothesized in the early 1960s that black holes would be found at the centers of some galaxies, and work in the 1980s identified a number of good black hole candidates, it fell to work conducted with Hubble to show that black holes are probably common to the centers of all galaxies. The Hubble programs further established that the masses of the nuclear black holes and properties of the galaxies are closely related. The legacy of the Hubble programs on black holes in galaxies is thus to demonstrate a deep connection between galaxies and their central black holes.

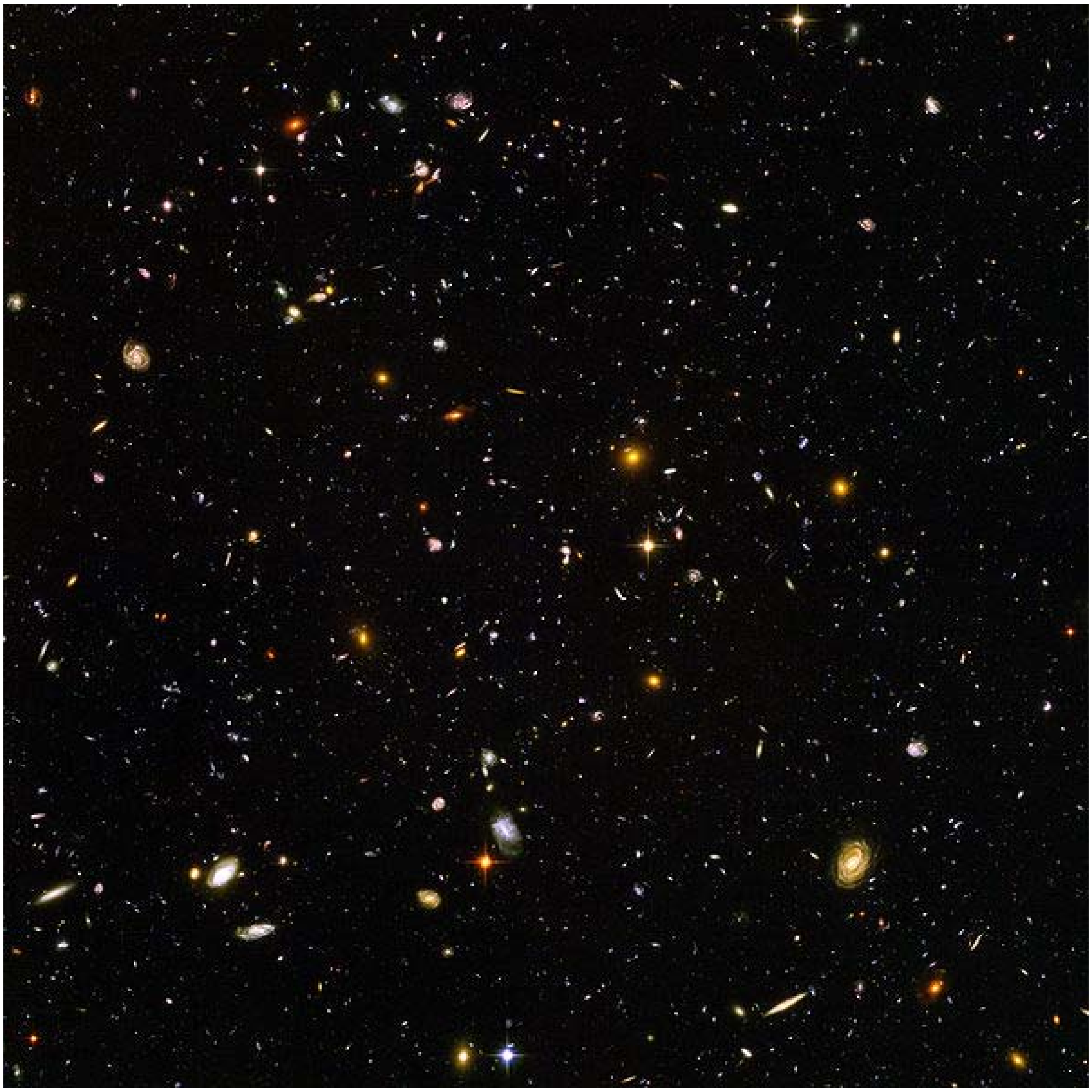
The collision of Comet Shoemaker-Levy 9 with Jupiter in 1994 was fortuitously timed for astronomers, coming just a few months after Servicing Mission 1 had restored Hubble's optical performance. Hubble images of the planet were sharper than any taken since the passage of Voyager 2 in 1979, and were crucial in studying the dynamics of the collision of a comet with Jupiter, an event believed to occur once every few centuries.

Other major discoveries made using Hubble data include proto-planetary disks (proplyds) in the Orion Nebula; evidence for the presence of extrasolar planets around sun-like stars; and the optical counterparts of the still-mysterious gamma ray bursts. HST has also been used to study objects in the outer reaches of the Solar System, including the dwarf planets Pluto and Eris.

A unique legacy of Hubble are the Hubble Deep Field and Hubble Ultra Deep Field images, which utilized Hubble's unmatched sensitivity at visible wavelengths to create images of small patches of sky that are the deepest ever obtained at optical wavelengths. The images reveal galaxies billions of light years away, and have generated a wealth of scientific papers, providing a new window on the early Universe.

The non-standard object SCP 06F6 was discovered by the Hubble Space Telescope (HST) in February 2006.

Impact on astronomy



Distant galaxies in deep space in a Hubble Ultra Deep Field photograph

Many objective measures show the positive impact of Hubble data on astronomy. Over 9,000 papers based on Hubble data have been published in peer-reviewed journals, and countless more have appeared in conference proceedings. Looking at papers several years after their publication, about one-third of all astronomy papers have no citations, while only 2% of papers based on Hubble data have no citations. On average, a paper based on Hubble data receives about twice as many citations as papers based on non-Hubble data. Of the 200 papers published each year that receive the most citations, about 10% are based on Hubble data.

Although the HST has clearly had a significant impact on astronomical research, the financial cost of this impact has been large. A study on the relative impacts on astronomy of different sizes of telescopes found that while papers based on HST data generate 15 times as many citations as a 4 m ground-based telescope such as the William Herschel Telescope, the HST costs about 100 times as much to build and maintain.

Making the decision between investing in ground-based versus space-based telescopes in the future is complex. Even before Hubble was launched, specialized ground-based techniques such as aperture masking interferometry had obtained higher-resolution optical and infrared images than Hubble would achieve, though restricted to targets about 10^8 times brighter than the faintest targets observed by Hubble. Since then, advances in adaptive optics have extended the high-resolution imaging capabilities of ground-based telescopes to the infrared imaging of faint objects. The usefulness of adaptive optics versus HST observations depends strongly on the particular details of the research questions being asked. In the visible bands, adaptive optics can only correct a relatively small field of view, whereas HST can conduct high-resolution optical imaging over a wide field. Only a small fraction of astronomical objects are accessible to high-resolution ground-based imaging; in contrast Hubble can perform high-resolution observations of any part of the night sky, and on objects that are extremely faint.