1975–1990

Space Telescopes for Astronomy

James Breckinridge

In 1946, Lyman Spitzer of Princeton University proposed the construction of a space telescope for astrophysics, and Princeton astronomers launched several balloon-borne telescopes (Stratoscope project) to operate in the dry excellent seeing provided by the upper stratosphere to demonstrate the value of space science.

At the very beginning of NASA, Nancy Roman, Lyman Spitzer, and Art Code laid out a space satellite program that envisioned a series of modest-aperture telescopes for UV and optical astronomy [the Orbiting Astronomical Observatory (OAO)] and an R&D program leading to a "large space telescope." The seeds of the Hubble Space Telescope were sown 35 years before its launch.

In 1962 the world's first space telescope was launched, and it recorded the UV spectrum of the Sun. The OAO program became a series of three space telescopes. The first OAO was to carry experiments, and observing time was to be shared between the two university groups that produced the instruments. However, when that satellite was launched, it almost immediately self-destructed before the scientific instruments could be turned on.

NASA quickly organized an additional launch using flight spares of the satellite and the scientific instruments. That satellite was successful and is referred to now as OAO-2. It was launched 7 December 1968, carried 11 UV telescopes, and operated until 1973. OAO-2 discovered that comets are surrounded by enormous halos of hydrogen several hundred thousand kilometers across and made observations of novae to find that their UV brightness often increased during the decline in their optical brightness.

OAO-3 (Copernicus) was orbited in August of 1972 and carried an 80-cm-diameter telescope for UV astronomy. OAO-3 successfully operated for 14 years and established an excellent reputation for the highest-quality astronomical data at the time. The Copernicus mission played a large role in winning the support of the wider astronomical community for space astronomy, not only because of the very high-quality data it produced, covering the UV to below the Lyman limit, but also because of the serious commitment Spitzer and his Princeton colleagues showed to making the data available and easily interpretable. Complete spectra were obtained for only about 500 stars, very modest by today's standards. But the scientific impact of those spectra was huge!

The concept for a series of four large telescopes, called the "Great Observatories," evolved at NASA starting in the 1980s. In order of increasing wavelength they were Compton Gamma Ray Observatory (CGRO), Advanced X-Ray Astrophysics Facility (AXAF), now called Chandra, the Hubble Space Telescope (HST), and the Space Infrared Telescope Facility (SIRTF), now called Spitzer. Optical Society (OSA) members had a major role in the development of AXAF, Chandra, and Spitzer.

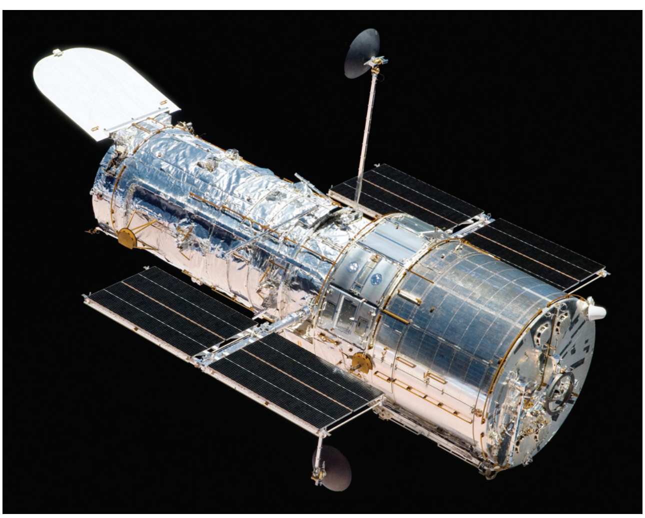
HST started out as the Large Space Telescope (LST) with a 3-meter aperture. Soon the reality of the launch vehicle capacity set in and NASA issued a request for information to the industry for a 2.4-meter-diameter telescope. Three optics companies, all corporate members of OSA, responded with feasibility studies: Eastman Kodak, Itek, and Perkin-Elmer. Perkin-Elmer was selected as the primary telescope provider. NASA recognized that the longest lead item in the procurement would be the primary mirror and directed Perkin-Elmer to fund Eastman Kodak to provide a back-up mirror. This mirror is now at the Smithsonian Air and Space Museum. Corning manufactured both of the ultra-low expansion (ULE) honeycomb 2.4-meter mirror blanks. PE was responsible for the telescope, and Lockheed Sunnyvale was the spacecraft system integrator.

“Large” was dropped from the LST name during its development, and later it was renamed after Edwin Hubble to become the HST. NASA Headquarters issued a competitive-science solicitation for instruments. These UV/optical/IR science instruments were designed to be replaced on-orbit.

The HST became the world’s first scientific instrument with the capability to be serviced multiple times on-orbit. The instruments selected were the Wide-Field Planetary Camera (WF/PC), the Faint Object Camera (FOC), the Faint Object Spectrograph (FOS), the Goddard High Resolution Spectrograph (GHRS), and the High Speed Photometer (HSP). The HST primary mirror was maintained near room temperature. That combined with the poor IR detectors at the time prohibited an infrared astronomy instrument.

HST was scheduled for launch in 1986 soon after the Challenger mission that ended in disaster. The shuttle fleet was grounded for 32 months, delaying the HST launch to late April 1990. By the end of May 1990 it was discovered that the telescope could not be focused, and in June the error was suggested to be spherical aberration. NASA headquarters formed two teams. One, the official NASA optical failure review board led by Dr. Lew Allen (a retired four-star general and JPL director) had membership and support from Optical Society Fellows Roger Angel, Bob Shannon, John Mangus, Jim Breckinridge, and Bob Parks. This team investigated the root cause of the error. The other board, the Hubble Independent Optical Review Panel (HIORP) was led by Optical Society Fellow Duncan Moore. Optical Society Fellows Aden and Marjorie Meinel, Dietrich Korsch, Dan Schulte, Art Vaughan, and George Lawrence, among others, were members. The HIORP had broad membership from the optics and astronomy communities and was charged with making recommendations on how to fix the error. The nation’s optics community came together to establish that the error was on the primary. Nine optics groups composed of many Optical Society Members and Fellows across the country made independent measurements on the PE test apparatus hardware and on digital images recorded by the hardware on-orbit. The recording of star images across the field of view and at different telescope focus settings provided a diverse set of image data for the new prescription retrieval algorithms. For the first time, the on-orbit optical prescription was determined precisely. The intensity of this work is evidenced by the fact that it was completed over a ten-week period to meet the instrument rebuild schedule for a repair mission launch.

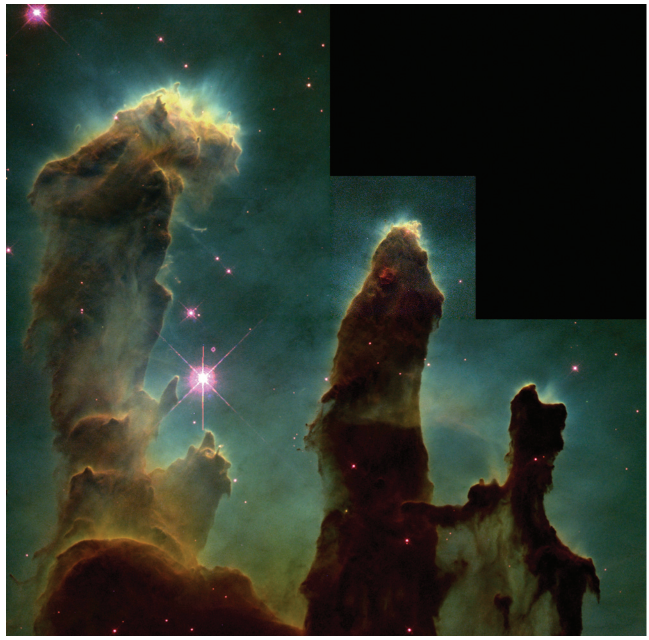
An accurate value for the telescope primary-mirror conic constant and the fact that the error was isolated to the primary enabled corrective optics to be integrated into a newly built WF/PC2 (designed and built by NASA/JPL), and a new optical system called COSTAR. COSTAR was designed and built by Ball, an Optical Society Corporate Member. Both instruments were inserted into HST on the first repair mission. The COSTAR optical system replaced the HSP instrument. This new optical system corrected the wavefront for the Faint Object Spectrograph (FOS), the Faint Object Camera (FOC), and the GHRS. In 1997 the IR system NICMOS was launched replacing COSTAR to give the telescope its first IR capability to 2-μm wavelength.



▲ **Fig. 1.** The HST in orbit. (Image courtesy of NASA.)

Today, at the one hundredth anniversary of The Optical Society, the HST has been successfully operating for 26 years. By far it is the most productive scientific UV/optical instrument ever known, a spectacular monument to the space optics community and the many dedicated Optical Society members who saved the mission from disaster. Figure 1 is a photo of the HST in orbit taken from the space shuttle after a service mission. One of the most famous and spectacular photos taken by HST is shown in Fig. 2. It is the so-called “pillars of creation” in the Eagle Nebula where stars, and by implication their exoplanet systems, are seen forming in the dust clouds.

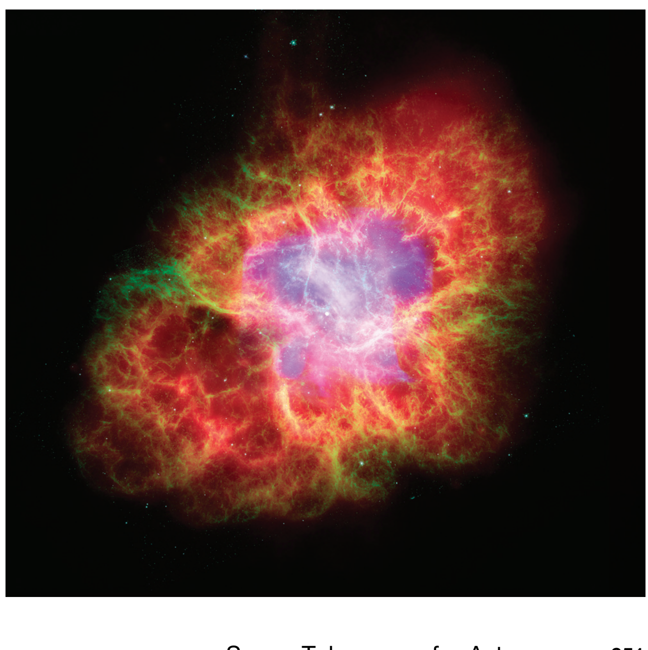
The x-ray telescope mission, Chandra, was launched in 1999, 33 years after the proposal by Riccardo Giacconi and Harvey Tananbaum. Chandra uses two sets of nested-cylinder mirrors in the hyperbola–parabola configuration of the Woljter type-2-configuration grazing-incidence x-ray telescope built by Eastman Kodak. Chandra's angular resolution is unmatched: between 80% and 95% of the incoming x-ray energy is focused into a 1-arcsec circle. Leon van Speybroek led the details of the optical design and the fabrication of the mirrors. Furthermore, x-rays reflect only at glancing angles, like skipping pebbles across a pond, so the mirrors must be shaped like cylinders rather than the familiar dish shape of mirrors on optical telescopes. The Chandra X-ray Observatory contains four co-aligned pairs of mirrors. Figure 3 shows an image of the Crab Nebula recorded with the ACIS instrument superposed upon an image recorded with HST to show the value of multispectral (visible and x-ray) imaging science.



▲ **Fig. 2.** The "pillars of creation." Star formation in the Eagle nebula photographed by the HST. (Image courtesy of NASA, ESA, STScI, J. Hester and P. Scowen [Arizona State University].)

Today, at the one hundredth anniversary of Optical Society, the Chandra has been successfully operating for 15 years, three times its design lifetime, and it remains in highly productive operation.

Much excellent IR astronomy from telescopes on the ground has been done through those spectral windows in the IR not absorbed by the Earth's atmosphere. However, many exciting astrophysics problems require the measurements of cold gas and dust available only using IR space telescopes, which measure the temperature of the universe and need to be colder than the sky they measure. Two major space cryogenic IR telescopes were designed, built, and launched to map the IR sky: the Infrared



▶ **Fig. 3.** This composite image uses data from three of NASA's Great Observatories. The Chandra x-ray image is shown in light blue, the HST optical images are in green and dark blue, and the Spitzer Space Telescope's infrared image is in red. The size of the x-ray image is smaller than the others because ultra-high-energy x-ray-emitting electrons radiate away their energy more quickly than the lower-energy electrons emitting optical and infrared light. The neutron star, which has mass equivalent to the Sun crammed into a rapidly spinning ball of neutrons 12 miles across, is the bright white dot in the center of the image. (X-Ray: NASA/CXC/J. Hester [ASU]; Optical: NASA/ESA/J. Hester & A. Loll [ASU]; Infrared: NASA/JPL-Caltech/R. Gehrz [Univ. Minn.])

Astronomical Satellite (IRAS) and Spitzer. Launched in 1983, the IRAS telescope system, whose scientific development was led by Gerry Neugebauer, was the first space observatory to perform an all-sky survey at IR wavelengths. Engineering and development of the optical system was completed at Ball Aerospace, an Optical Society Corporate Member, teamed with Steve Macenka, an Optical Society Fellow, at JPL. IRAS discovered over 350,000 new sources, including stellar gas and dust envelopes now known to be the birthplaces of exoplanet systems, some possibly similar to our own solar system. The Spitzer telescope system, the fourth and final telescope in the Great Observatory series, was launched in 2003 into an Earth-trailing orbit. The primary, secondary, and metering structure are all fabricated from berylium. The optics were configured at Tinsley, and cryo testing was carried out at JPL. Diffraction-limited imaging at 6.5 μm over a 30-arc-min field of view was achieved.

By the year 2000, plans were underway to build an even larger space telescope, and NASA funded the Next Generation Space Telescope (NGST) study, which led to the James Webb Space Telescope (JWST), now scheduled for launch in 2019, in time to start the second hundred years of The Optical Society. John Mather, Nobel Prize Laureate in Physics 2006 and Optical Society Fellow, was the chief scientist for the project during its formative years. This telescope builds on the success of the large ground-based segmented telescopes, e.g., Keck. Telescopes with segmented primary mirrors that are mechanically deployed once the spacecraft is in orbit make possible very large space telescopes.

Recently several smaller space optics systems have revolutionized our understanding of the universe. These are: WISE, COBE, GALEX, Herschel, Planck, WIRE, WISE, and WMAP. The SOFIA is a 3-meter telescope mounted in a B747 for IR observations above the atmosphere. The Kepler space telescope launched March 2009 is a 0.95-meter clear-aperture Schmidt camera precision radiometer that contains arrays of CCDs totaling 95 megapixels staring at 140,000 stars across a FOV of 105 deg^2 in the constellation of Cygnus. The Kepler mission has discovered several thousand exoplanets and will continue to revolutionize our understanding of the evolution of planetary systems, stellar atmospheres, and stellar interiors as the enormous database is analyzed in detail over the coming decade.

Today one of the most exciting space optics programs is the design and construction of hyper-contrast optical systems to characterize exoplanets in the presence of the intense radiation from the central star of the exoplanet system. Terrestrial planets are 1 part per trillion as bright as the central star. Spectrometric measurements are required of the radiation reflecting and emitting from the exoplanet. These measurements provide data to estimate planetary surface and atmospheric composition! Direct observation of rocky terrestrial planets, which might harbor life as we know it, requires large-aperture telescopes. This is an opportunity to answer one of humanity's most compelling questions: Are we alone in the universe?

In addition to using spectrometric measurements to resolve the question of composition, optical spectrometers are also used to determine the radial (along the line of sight) velocity as a function of time to an accuracy of centimeters per second. Precision optical astrometry is used to determine the motion of stars across the sky to precisions approaching microarcsec. These two measurements provide the data we need to calculate the orbit of the planet about its parent star.

Direct images and spectra of exoplanets at contrast levels of 10^{-10} are needed so astronomers can record the light reflected from the exoplanet and search for life signatures in the atmosphere and on the surface. All of these require new-technology optical systems operating in the harsh space environment out from under the turbulence of the Earth's atmosphere. Today, astronomical science, enabled by innovative optical telescope and instrument design, is on the threshold of revealing details on the evolution of the universe and the presence of life beyond Earth.

The JWST is the largest space optical system under construction now. It represents the state of the art in optical design, engineering, fabrication, and testing. The JWST will replace the spectacularly successful Hubble Space Telescope with a much more capable system promising further astounding discoveries.