The Hubble Space Telescope (HST) is now ready to be bundled on the Space Shuttle Discovery. Preparations are being made to deploy it into a circular orbit 610 km above the Earth's surface, where it will begin its duties as the world's premier optical astronomical observatory.

The telescope is named to honor the astronomer Edwin P. Hubble who, in 1929, first announced the fundamental fact that our universe expands. Hubble made his discoveries using the most advanced telescope of his day—the 100-inch telescope on Mt. Wilson in California. The HST is nearly the same size as Hubble's, but with a performance an order of magnitude better than he could have dreamed. It is fitting that this new powerful tool of astronomy, which will be used for exploring the structure and history of the universe, is named after the man who first discovered much of the universe's complexity.

The launch will be the culmination of a quarter century of planning and preparation, undertaken jointly by NASA, the European Space Agency (ESA), astronomers and industry in both North America and Europe. In 1965, the prominent astronomer, Lyman Spitzer, obtained the backing of the National Academy of Sciences' Space Science Board to form an ad hoc committee to consider the performance criteria and technologies needed for a large observatory in space. Spitzer had been the first to propose formally, in 1946, that a valuable objective of post-war rocket technology would be to place an astronomical observatory above the Earth's atmosphere.

Although NASA developed a series of Orbiting Astronomical Observatories (OAOs) during the 1960s capable of carrying telescopes up to one meter in diameter, these had limited instrumental and scientific objectives. It was due to Spitzer's vision and persuasion that serious studies were begun of a large space-based astronomical telescope before the first successful OAO even reached orbit. After evaluating many alternatives, Spitzer's committee decided

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**FIGURE 1.** An early concept for the space telescope. This concept has an extendible sunshield forward. The instrument compartment contains a large steerable mirror to direct the collimated telescope beam to several instrument locations. The compartment can also be pressurized for "shirt-sleeved" astronaut maintenance.

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that Earth orbit was preferable to a lunar base, advocated replaceable instrumentation and manned maintenance while emphasizing the great difficulties associated with manned operation, identified necessary new technologies, and proposed a schedule that would have led to a launch in 1979.4

While Spitzer’s group was at work, NASA began a series of studies on a large manned observatory, beginning with a feasibility study done by Boeing for the Langley Research Center. This study adopted 3 meters as the size of the primary, on the basis that this was the largest mirror that could be launched by a Saturn-class rocket, the only launch vehicle available at the time. Throughout its subsequent study phases, the Large Space Telescope (as it was then called) was assumed to have a 3-meter aperture.

During the late 1960s, NASA supported technology developments in optics and detectors. The agency and its contractors also examined many different concepts for the observatory. At one extreme was a completely automated observatory to be visited and serviced only by remote manipulators under interactive control by ground-based operators. Other studies went equally far in the other direction, describing telescopes orbiting in close proximity to a space station and being visited frequently by astronauts. One concept, illustrated in Fig. 1, showed an observatory containing a large hermetically sealed work space where astronauts would have a “shirt-sleeve” environment for tasks such as changing film packs to be returned to the space station for development and analysis.

In 1970, competing Phase A studies were begun at the Marshall and Goddard Space Flight centers, which culminated in the 1972 selection of Marshall as the lead center for the project. Goddard was to be responsible for development of the scientific instruments and for the ground operations system. The formal Phase B Design Study began in 1973 when Marshall initiated telescope design contracts with Perkin-Elmer and Itek and let contracts to several aerospace companies to develop spacecraft designs.

**Primary aperture reduced**

At the same time, NASA selected teams of scientists to
Another decision crucial to the development of the instruments was that the focal plane should be shared...

provide preliminary designs of several candidate instruments, including cameras and spectrographs for visible and ultraviolet wavelengths and an infrared photometer. The team leaders and other "multi-disciplinary" scientists formed a Science Working Group to monitor the studies on the telescope and spacecraft. Most of the major decisions that were to shape the final HST were taken during this period.

Perhaps the most important of these decisions was to reduce the primary aperture from 3 meters to 2.4. Although a 3-meter telescope could be put into the shuttle bay, it was a tight fit and required that the major spacecraft components be located at the extreme aft-end. The smaller mirror allowed room for spacecraft boxes to be mounted circumferentially around the telescope's mid-section, greatly improving the mass distribution of the satellite. There were many other advantages. For instance, the mirror fabrication and testing were simplified and the weight was greatly reduced. Also, the shorter telescope structure made it possible to put a fixed solar baffle up front, rather than a complex and heavy extendible sunshield.

A second important decision was to organize most of the scientific instruments into standardized, interchangeable modules whose mechanical and electrical interfaces with the telescope and spacecraft are identical and easily reproduced. This not only greatly simplified the development and testing of the original instruments, but also made possible the development of advanced, replacement instruments with confidence that they will work properly when inserted into the HST on orbit.

Another decision crucial to the development of the instruments was that the focal plane should be shared, with each instrument having full-time access to the designated portion of the field. Alternatives that had been considered were to physically move instruments from their stowed positions into the on-axis observing position or to use articulated mirrors to redirect the telescope image to the selected instrument. With the shared focal plane there are no moving parts, the best-quality on-axis portion of the image is directed by a pick-off mirror to the Wide Field and Planetary Camera (Fig. 2), and the other four instruments have access to portions of the field where the only significant aberration is astigmatism, easily corrected within the instrument optics. Three arcs at the edge of the field are used by the three fine guidance star trackers. To control the telescope within its guidance specification, any two of the trackers must be locked onto guide stars located within these zones. The third Fine Guidance Sensor, which is carried as a spare, can also be used to measure accurate astrometric positions of stars within its field of view.

In 1975, when the European Space Agency agreed to provide solar arrays and one science instrument in return for about 15% of the observing time, the HST became an international project. By the end of the study phase in 1976, the design and performance characteristics of the spacecraft were essentially as they exist today (see Table 1 and Fig. 3). The telescope design called for an f/24 Ritchey-Chretien figure specified to produce a FWHM image of 0.056 arc second and a 70% encircled energy radius of 0.1 arc second at the test wavelength of 633 nm, with the expectation that substantially better images would be achieved at shorter wavelengths. All aspects of the structural and thermal design of the spacecraft have been driven by this optical specification. Even the electrical power budget is affected because the dynamic characteristics of the solar arrays are the dominant factor in meeting the fine guidance jitter requirement of seven thousandths of a second of arc. The present solar arrays are as large as they can be without degrading the telescope pointing.

TABLE 1. Hubble Space Telescope spacecraft characteristics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>13 m</td>
</tr>
<tr>
<td>Diameter (without arrays)</td>
<td>4.3 m</td>
</tr>
<tr>
<td>Mass</td>
<td>11,500 Kg</td>
</tr>
<tr>
<td>Power</td>
<td>2,400 w</td>
</tr>
<tr>
<td>Communications</td>
<td>$10^6$ bps through TDRSS</td>
</tr>
<tr>
<td>Tracking accuracy</td>
<td>0.01 arcsec</td>
</tr>
<tr>
<td>Tracking jitter</td>
<td>0.007 arcsec rms</td>
</tr>
<tr>
<td>Instrument arrangement</td>
<td>1 on-axis camera</td>
</tr>
<tr>
<td></td>
<td>4 near-axis instrument compartments</td>
</tr>
<tr>
<td></td>
<td>3 off-axis star trackers</td>
</tr>
</tbody>
</table>
FIGURE 3. Drawing of HST in orbit. The cut-away sec­
tion reveals the telescope’s graphite-epoxy truss structure
that supports the secondary spider forward and the pri­
mary strong ring aft. There is extensive internal baffling
for control of scattered light. Visible behind the primary
are two of the three star trackers and the cluster of four
near-axis instruments, all of which are replaceable on or­
bit. Deployed externally are the two large solar arrays
and two articulated antennae that track and communi­
cate with the Tracking and Data Relay Satellites.

Construction begins

The construction phase began in 1977, when Marshall
selected Perkin-Elmer to build the telescope and the Fine
Guidance Sensors, and Lockheed Missiles and Space
Corp. to build the spacecraft support systems and to as­
semble and test the complete satellite. An initial set of five
scientific instruments was chosen the following year from
proposals submitted by scientist teams. These are de­
scribed in the accompanying article.

The initial focus of attention was on the construction of
the telescope itself and particularly on the fabrication of
the primary mirror. Since the key to the entire HST was
the performance of the mirror, NASA hedged its bets by
procuring two blanks, made of ULE honeycomb sand­
wiches, and figuring one of them at Perkin-Elmer and the
other at Eastman Kodak. Although Eastman made excel­
gent progress on its mirror, the final polishing was stopped
at about \( \lambda/50 \) when it became apparent that the Perkin-
Elmer mirror would exceed its specification and produc­
sion schedule.

The mirror was completed in 1981 and has been mea­
sured to have an rms wavefront error of better than \( \lambda/65 \).
While the mirror was stored awaiting completion of the
telescope structure, a significant amount of dust and other
particulates were found to have accumulated on its sur­
face. After considerable debate about the risk of cleaning
the mirror versus the performance degradation that would
result from leaving it alone, the mirror was finally cleaned
in 1984 with a specially devised jig to blow particles off
the mirror and then vacuum them away. Careful monitor­
ing of the dust on the mirror surface over the past five
years shows that it has been kept remarkably clean since
that time.

Although the figures of the primary and secondary mir­
rors have been carefully measured individually, it is worth
noting that the image quality of the assembled telescope
will not be tested until the observatory is in orbit. The
calculated performance is given in Table 2, but test facili­
ties are not available to verify these numbers. However, if
things should not go according to plan, the fine guidance
assemblies within the telescope contain interferometers to
measure wavefront error on orbit and, if necessary, 24
pressure actuators at the back of the primary mirror can
be used to adjust its figure. In addition, the secondary mir-

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<table>
<thead>
<tr>
<th>Table 2. Hubble Space Telescope optical characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Telescope figure</td>
</tr>
<tr>
<td>Primary aperture</td>
</tr>
<tr>
<td>Primary focal ratio</td>
</tr>
<tr>
<td>System focal ratio</td>
</tr>
<tr>
<td>Plate scale</td>
</tr>
<tr>
<td>RMS wavefront error</td>
</tr>
<tr>
<td>Predicted on-axis image, including 0.007 arcsec rms jitter</td>
</tr>
<tr>
<td>Wavelength</td>
</tr>
<tr>
<td>633 nm</td>
</tr>
<tr>
<td>450</td>
</tr>
<tr>
<td>350</td>
</tr>
<tr>
<td>200</td>
</tr>
<tr>
<td>122</td>
</tr>
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</table>
ror can be moved with six degrees of freedom to optimize the image.

In 1984, the complete telescope assembly was shipped from the Perkin-Elmer plant in Danbury, Conn., to the Lockheed plant in Sunnyvale, Calif., to be incorporated into the spacecraft. The pace of assembly and testing became more and more intense as the 1986 launch date approached. Sadly, the Challenger explosion at the beginning of that year put all plans on indefinite hold.

The period since 1986 has been put to good use. ESA has rebuilt the solar arrays to improve performance and NASA has procured superior batteries so that these two items, which had originally been designed to require service every two-and-a-half years, now have lifetimes of five years or more—very substantially reducing long-term maintenance costs. Modifications have also been made to some of the scientific instruments and spacecraft subsystems, so that the HST is now impressively more capable than the one that would have been launched in 1986.

**Why an astronomical observatory?**

Why have astronomers from all over the world so eagerly awaited the opportunity to use this new telescope? There are three major reasons for placing an astronomical observatory above the influence of the Earth’s atmosphere: it avoids atmospheric absorption that limits optical telescopes on the ground to visible wavelengths plus some discrete bands in the infrared; it avoids the atmospheric emissions, or airglow, that contribute a background signal to ground-based images equivalent typically to the brightness of a 22nd magnitude star; and it avoids atmospheric turbulence that limits the spatial resolution of most ground telescopes to about 1 second of arc and renders images unstable on short time scales. For these reasons, telescopes in space can observe broader regions of the spectrum, can observe fainter objects, and can achieve higher spatial and temporal resolution than is possible from the ground.

HST’s advantage in spectral coverage will be used initially in the ultraviolet. All five instruments are sensitive down to the telescope’s short wavelength cut-off at about 110 nm. This wavelength region is of major interest astrophysically. It contains strong spectral lines of the most abundant and important elements—hydrogen, helium, carbon, nitrogen, and oxygen—and it includes the maximum energy emission for most classes of hot stars. Consequently, HST data will play a major role in modeling the plasmas found in places such as stellar chromospheres, expanding shells of supernovae, and the outer zones of quasars. The ultraviolet data will also be valuable in population and evolution studies of stars in distant galaxies.

At the other end of the spectrum, only one of the initial cameras has an extended red response out to about 1,000 nm. This situation will change with the completion of a new instrument already under development for on-orbit insertion into the observatory about five years after launch. This instrument will obtain images and spectra in the infrared out to about 4,000 nm. In this range, the combination of high image quality and good sensitivity will permit valuable studies of star-forming regions and perhaps proto-solar systems.

The reduced background emission in orbit and the tight point spread function will allow the HST, which has a rather modest aperture by modern astronomical standards, to be fully competitive in sensitivity with the largest telescopes currently planned for ground observatories. This ability to observe very faint objects, combined with HST’s high spatial resolution, will permit studies of very complex fields, such as the structures of quasar and galaxy nuclei and the details of solar system objects such as asteroids and the surface of Pluto, the only planet unexplored by an interplanetary probe.

**Spectacular spatial resolution**

The most spectacular of HST’s capabilities will be its spatial resolution. The telescope is expected routinely to achieve about a factor of 10 better resolution, corresponding to 100 times more information content, than is obtained from the ground. Figure 4 puts this gain into histor-

![Figure 4. The change in astronomical imaging capability with time. Since the invention of the telescope, the resolution achieved by optical astronomers has been limited largely by atmospheric turbulence. HST orbiting above the atmosphere will produce a dramatic improvement in image quality, comparable to the difference between Galileo's telescope and the naked eye.](image)
After launch, the HST will require about three months of engineering check-out . . .

ic context. The human eye can resolve about a minute of arc, and that represented the state of astronomical technology until 400 years ago when Galileo built his first telescope. Galileo's most exciting discoveries were not the result of his instrument's increased light-gathering power, but because of its increased resolution. In the centuries since then, we have made only marginal improvements on that resolution because of the serious limitations caused by atmospheric turbulence. Now there is the opportunity to make the same order-of-magnitude improvement in capability that Galileo achieved.

An example of how this improvement may be used is in the search for black holes. Although black holes are now widely accepted as expected and even necessary members of the space zoo, there is still no unambiguous evidence that such things actually exist. Since they are indeed completely black and much too small to cast a shadow visible to our telescopes, they can be detected only by indirect means such as the intense energy radiated from matter being accelerated into the singularity. In the case of a massive black hole at the center of a nearby galaxy, this emission would come from a zone not much larger than the black hole itself, and so appear to be point-like even at extremely high resolutions. All other possibilities for the bright nuclear emission, such as very dense clouds of bright stars, would appear as a broad extended region to the high resolution HST cameras. Thus, our first proven black hole may come from an HST image showing a sharp cusp of light at the center of a galactic nucleus.

After launch, the HST will require about three months of engineering check-out before it can acquire its first data of scientific quality. Following that will be a period devoted to radiometric and other calibrations, mixed with scientific observations by the astronomers responsible for construction of the instruments. Finally, about eight months after launch, the observatory should be ready to start its career as a general research facility. The research program will be managed for NASA by the Space Telescope Science Institute at The Johns Hopkins University in Baltimore, which will construct the observing schedule from an annual selection of proposals submitted by scientists worldwide.

One cannot anticipate the new discoveries of HST any better than Galileo did when he first pointed his telescope at the sun and planets, but one can be confident that they will open an exciting new chapter in our study of the universe.

REFERENCES