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No. 16 - Winter 1990

The Latest News on the *Hubble Space Telescope*: Flawed but Working and Fixable

During the past spring and summer, the eyes of the astronomical community were riveted on the dramatic news of the *Hubble Space Telescope* (*HST*). Launched into perfect orbit after long delays, the telescope began its months-long engineering check-out phase with everyone's hopes held high. Then came the shocking revelation: due — it appears — to an error at the company that manufactured its pioneering mirror, the telescope had a major flaw. The flaw sounds minor at first hearing: the mirror is the wrong shape by about 1/50th the width of a human hair. Yet that small aberration is enough to endanger a wide variety of projects planned with the telescope — at least until astronauts can go back in a few years and make repairs. We devote this issue of *The Universe in the Classroom* to *HST* — its potential, its problems, and its current status.

- What kind of telescope is *HST* and what was it designed to do?
- Since we already have bigger telescopes on the ground, why bother with a 94-inch telescope in space?
- What specific instruments will be used to analyze the light *HST*'s mirror gathers?
- What scientific projects is *HST* going to undertake?
- What exactly happened with *HST*'s mirror?
- How does the mirror flaw affect the working of the telescope?
- Can the problem be fixed?
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What kind of telescope is HST and what was it designed to do?

The *Hubble Space Telescope* is the largest and most complex telescope ever put into orbit. It is a *reflector*, which means it uses a mirror to collect light and bring it to a focus. *HST*'s main mirror is 2.4 meters (94 inches) in diameter and is made of titanium silicate glass, which does not expand or contract very much when it is heated or cooled. (That's important because the telescope orbits the Earth every 96 minutes, and goes through a "day'' and a "night'' during each orbit.) There are a number of larger reflecting mirrors used for astronomy on Earth — the famous telescope on Mount Palomar in Southern California has a 5-meter (200-inch) mirror and the new Keck Telescope, soon to start operations in Hawaii, will boast a 10-meter mirror when all its segments are in place. But the *HST* has the distinct advantage of being in space, above the often murky, jittery, and glowing layers of our planet's atmosphere.

HST's mirror is also the smoothest ever made: if the 94-inch mirror were scaled up to be the size of the United States, the surface would have no imperfections greater than 2.5 inches! It took 150 person-years to create a mirror that smooth — which is why astronomers were so concerned that the ultimate curve of the mirror turned out to be wrong.

Since we already have bigger telescopes on the ground, why bother with a 94-inch telescope in space?

Observing the universe from the surface of the Earth is like trying to watch a game of baseball from the bottom of a swimming pool. Even if the players are all in view, from your vantage point under the water the details of the game can be hard to make out.

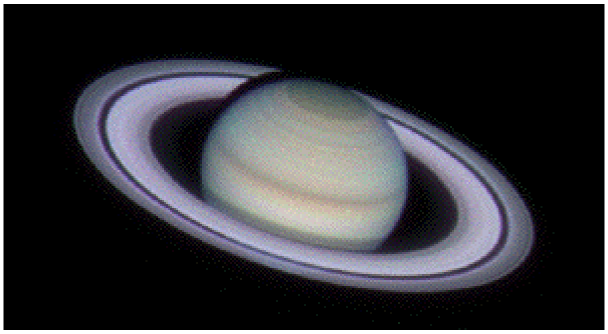
The many layers and pockets of air above us are in constant motion and the resulting jiggling of the atmosphere not only makes stars twinkle, but also makes the images we see of all celestial objects look fuzzy. Typically, the Earth's atmosphere spreads out star images from a sharp point to a fuzzy patch one *second of arc* in diameter. (A second of arc is roughly the size of a dime as seen from two miles away.) While that sounds pretty small, for frontier astronomical projects, when we are trying to see the inner details of some complex galaxy or just trying to separate two stars that are very close to each other in a crowded cluster, we need to do much better than that. Up in space, above the atmosphere, *HST* should be able to show images that are 10 times sharper. Astronomers call the telescope's ability to see detail its *resolution* — and *HST*'s better resolution was a major factor in the decision to build it.

In addition, putting the telescope above the Earth's atmosphere helps to reduce the background glow of light that enters the instrument. Here on Earth, the layers of air above us glow at night, both by scattering the light from the Moon and the stars, and also by producing their own light as charged particles from space hit the atmosphere's upper layers. This "sea of background light'' is very faint, but becomes a crucial "barrier'' for astronomers trying to observe the even fainter light of distant objects.

With *HST*, we can literally rise above this problem, some 380 miles above the Earth's surface. Because there is no twinkling of the images, astronomers using *HST* will also be able to measure the rapid variations of cosmic objects much more precisely than from the ground. And last, but certainly not least, *HST* will be able to detect forms of light that our atmosphere filters out. Primary among these will be *ultraviolet* light — a little of which gets through to give suntans to those Earthlings not protected by dark skin-coloring — but most of which is absorbed in the ozone layer. Yet many celestial objects, often those which are most violent and energetic, give off ultraviolet light and we are eager to learn more about the cosmos by studying it.

What specific instruments will be used to analyze the light HST's mirror gathers?

Collecting the light and bringing it to a focus is only the first step in doing astronomy. Then the light has to be recorded and analyzed to understand the messages it is bringing us from distant stars and galaxies. *HST* has six instruments to which its light can be directed: two cameras, two *spectrographs* (instruments for spreading out the light into a spectrum), a high speed *photometer* (a fast, accurate light meter), and "fine guidance sensors'' for measuring the positions of stars with unprecedented accuracy.



This image of Saturn was taken with HST's Wide Field/Planetary Camera Aug. 26, 1990, when Saturn was 1.4 billion km (860 million mi) from Earth. It and other HST photos show the ringed planet with almost as much clarity as the Voyager flyby images. (Courtesy NASA/Goddard)

There are two cameras on board *HST* because each is designed to do different kinds of work. The Wide Field and Planetary Camera (WF/PC) is designed to look at brighter objects and wider fields of view. It has already sent back the spectacular photograph of the planet Saturn seen to the right. The Faint Object Camera (FOC), as its name implies, is designed to see the faintest objects in the universe, but also to show the most detail possible. Both cameras will record the images they form not on film, but on extremely sensitive electronic light detectors called *charge-coupled devices* (CCD's).

In fact, such CCD light detectors are part of a quiet development in technology that is revolutionizing astronomy on the ground as well as in space. A piece of film records only a small fraction of the light that falls on it; in contrast, as much as 70% of the light can be recorded by a CCD. The WF/PC is equipped with a CCD detector that can record the light falling onto 256 million individual picture elements (pixels, as scientists call them). This camera will be on whenever the telescope is operating, translating the precise amount of light hitting each pixel into a digital readout that will be sent back to Earth regularly. Over the years, the output of this instrument will form a permanent record of what *HST* "saw'' as its other instruments scan the universe.

The FOC also uses an electronic light detector, but it adds another technological twist to the light. Inside the camera are state-of-the-art *image intensifiers* — essentially light amplifiers that can take the faintest bits of light and make them brighter without changing them. In principle, these devices work the same way as the amplifier in your home stereo system, which takes the weak signal produced by the cartridge in the turntable and makes it strong enough to blast the neighbors with the full impact of Tchaikovsky's *1812 Overture*. Similarly, the modern light amplifiers can take the very weak light signals from remote objects and — without altering the precious information they carry — can amplify them to be as much as 100,000 times brighter than the original light.

What scientific projects is HST going to undertake?

It would take several issues of this newsletter to discuss the many projects astronomers hope to carry out during *HST*'s 15-year lifetime. Proposals have come in to undertake research in almost every branch of astronomy — looking at objects as close as Mars and as far away as the farthest known *quasars*, the most remote objects in the universe, thought to be the energetic centers of newly forming galaxies, seen as they were billions of years ago.

Here are just a few of the projects that will eventually be done with *HST*, to give you a taste of what's being planned:

- How does the weather on Jupiter change with time and what can the continent-sized storm systems in its fast-moving atmosphere tell us about weather on Earth?
- Are there planets around other stars?
- What sorts of stars explode at the end of their lives, and which stars end their existence in more peaceful ways?
- How soon after the Big Bang did galaxies of stars start to form?
- Are there giant *black holes*, places where gravity has overwhelmed everything, at the centers of all galaxies or are they limited to certain types of galaxies?
- How important is *galactic cannibalism* (where a larger galaxy swallows a smaller neighbor) to the evolution of galaxies in clusters?
- How old is the universe and will it expand forever or someday contract?

What exactly happened with HST's mirror?

It appears that when the mirror was being polished to the right shape, the device used to test its curvature — called a *null corrector* — had been made to the wrong specifications. Thus, when the null corrector showed that the *HST* mirror was as close to perfect as it could be, it was actually ever so slightly the wrong shape.

This kind of error in making mirrors is called *spherical aberration*, and it is so well known that it appears in just about every introductory astronomy textbook. What it means is that the the light being collected from across the mirror does not come to a focus at a single point as it is supposed to. Instead, light rays hitting the edge of the mirror focus to a point about one inch away from the where light rays from the mirror's center focus.

How does the mirror flaw affect the working of the telescope?

To make images significantly sharper than can be done from Earth, *HST* was supposed to concentrate 70% of the light from a star into a very narrow "core'' of light. With the mirror problem, only about 15% of the light is concentrated into this narrow core — the remainder is spread out into a less sharp "halo'' of light that is about as large as the best images we can get from the ground (about one second of arc.) In other words, the majority of the image is fuzzy, and only a small fraction of the light is as sharp as *HST*'s designers had hoped.

Now here is the good news: if you are observing a bright object, you can afford to throw away much of the light — and only use the part that is in sharp focus. Modern computer processing techniques can let you do away with the fuzziness and just use the light in the core. But since *HST* was supposed to look at many objects that are so faint we can barely detect them, there will be many situations where astronomers will need every bit of light they can collect. In that case, the halo cannot be processed out, and — until repairs can be made — we will have to be content with a fuzzy image. (Actually, each of the *HST*'s instruments is affected by the mirror problem in a slightly different way. Experts associated with each instrument, as well as experts in the computer enhancement of astronomical images, are now studying the workings of each instrument to see what can and can't be done.)

In the meantime, engineers report that, ironically, all the electronic systems and all six of the main instruments aboard the telescope seem to be working as well or better than had been planned. (There is still a wobble which seems to be caused by the solar panels reacting to changes from darkness to light, but engineers hope to have its effects minimized by changes in the commands issued to the telescope.) All of this makes the mirror flaw even more frustrating to those astronomers who have spent over a decade designing the instruments for NASA and were hoping by now to reap the rich rewards of being given "first dibs'' on the most exciting astronomical problems of our day.

Can the problem be fixed?

Without bringing the whole telescope back to Earth, nothing can be done at this point to fix the mirror itself. All the solutions now being considered involve doing something with the light *after it* has reflected off the main mirror, but before it reaches the light detecting devices in each instrument.

Luckily, because the mirror error is so uniform and large, it does not seem to be difficult to put correcting lenses or mirrors into the light path or the instruments to undo the damage the mirror flaw has caused. Unfortunately, such "contact lens'' correctors cannot be put on the existing instruments because the astronauts cannot handle tiny mirrors or lenses with their bulky space-suit gloves. But even before the flaw was discovered, NASA had already made plans to bring up a new improved Wide Field and Planetary Camera and insert it into the telescope in 1993. (All the instruments were designed to be modular for easy removal and replacement in case they suffered problems.) Astronomers at Caltech and the Jet Propulsion Labs who are working on the new generation camera report that they should have no problem in designing the new system with just the right error to cancel out the problem the main mirror is causing.

Other instruments, now planned for a 1996 Shuttle mission, can also be designed to compensate for the mirror problem and thus deliver sharp images once again. As this issue was going to press, engineers were also looking at a more dramatic plan to replace one of the instruments with a "black box'' with a sort of "robot arm'' that would extend correcting optics into the light beam reaching *all* the other instruments.

What can be done in the meantime?

Some of the projects planned for the first few years of *HST* operations, especially those dependent on seeing the greatest detail in very faint objects or in crowded fields of view, will have to be postponed until repairs can be made. But many other projects can go ahead as planned, especially if each observation is given more time on the telescope, so that more light can be gathered. Teams of astronomers are going over the details of the observing schedule to make best use of the telescope's current abilities. Certainly, everyone involved with *HST* hastens to point out that media stories discussing the complete failure of the telescope were grossly exaggerated. *HST* may be flawed but it is not broken!

While the scientific work of the telescope is just beginning, the cameras have already sent back some spectacular photographs, including the best image yet of the distant planet Pluto and its mysterious moon Charon and a pioneering view of the center of a complex cluster of stars at the heart of the Tarantula Nebula. We will keep our readers informed about the progress of *HST* in future issues of *The Universe in the Classroom*.

For Further Information

- Field, G. and Goldsmith, D. *The Space Telescope: Eyes Above the Atmosphere*. 1990, Contemporary Books. The best introductory book about *HST*. (A section was adapted into an article in Mercury magazine, Mar/Apr. 1990, p. 34.)

- Smith, R. *The Space Telescope*. 1989, Cambridge U. Press. A scholarly history of the *HST* project.
- The April 1990 issue of *Sky & Telescope* magazine was devoted to *HST* and has several good articles about all aspects of the project.
- Marant S. "The Promise of the *Hubble Space Telescope*'' in *Astronomy*, Jan 1990, p. 38.
- Villard, R. "The Space Telescope at Work'' in *Astronomy*, June 1989, p. 38.

Articles on the Mirror Problem and Solutions:

- Begley, S., et al. "Heaven Can Wait'' a cover story in *Newsweek*, July 9, 1990, p. 48.
- Fienberg, R. "Space Telescope: Picking Up the Pieces'' in *Sky & Telescope*, Oct. 1990, p. 352.
- Villard, R. "The *Hubble Space Telescope*: Problems and Solutions'' in *Mercury*, Sep/Oct. 1990, p. 141.
- Waldrop, M. "Astronomers Survey Hubble Damage'' in *Science*, July 13, 1990, p. 112; "The Case of Single Point Failure'' in *Science*, Aug 17, 1990, p. 735.

How To Get Slides of the Images from *HST*

A slide and information kit with 25 images taken of and with the *Hubble Space Telescope* is now available from the nonprofit Astronomical Society of the Pacific. Assembled with the assistance of the Education Staff at the Space Telescope Science Institute (and a number of other NASA centers and aerospace companies), the set includes:

- paintings and diagrams showing *HST* operations, instruments, and repair
- photos of *HST*'s deployment taken by the astronauts
- the first set of *HST* camera images, including Saturn, Pluto, the Einstein Cross, the center of the Tarantula Nebula, the ring around Supernova 1987A, etc.

The slides are accompanied by an extensive booklet with nontechnical background information, detailed captions, and a thorough *HST* reading list.