THE TROUBLE WITH HUBBLE

A nine-year-old blunder threatens the mission of the most sophisticated orbiting satellite ever launched. How did it happen? Can Hubble still delve the cosmos?

By ARTHUR FISHER

It should have been the greatest leap forward in astronomy since Galileo. It should have seen farther, deeper, and more acutely into space and time than any instrument the hand of man had fashioned.

Perhaps it will, some day. But for now, the Hubble Space Telescope, an orbiting satellite that whirls around Earth 16 times a day, is a myopic Cyclops, its fuzzy vision caused by a fatal flaw in its 94-inch primary mirror. It is a staggering disappointment to astronomers everywhere, a red-faced embarrassment for NASA and its contractors, a major setback for the backers of big space projects and for the lawmakers who had appropriated the $1.6 billion investment in Hubble, and another blow to the taxpayers—already sensitized by space shuttle failures —whose pockets had supplied the dollars.

"It's a tragedy, it's incredibly disappointing," moaned Sidney C. Wolff, director of the National Optical Astronomy Observatories in Tucson, Ariz. "We had planned to get a whole new view of the universe."

Princeton University astronomer James Gunn, who had hoped to use one of Hubble's high-resolution cameras to obtain revealing images of distant galaxies and quasars, sent an outraged tirade by electronic mail to colleagues, calling the Hubble "fiasco" "probably the most expensive scientific failure in history," and blaming the astronomical community for allowing NASA and the aerospace industry to manage scientific projects.

Sen. Albert Gore, chairman of the subcommittee on science, technology, and space, said: "NASA's eyes are bigger than its stomach. We owe it to the taxpayers to find out what went wrong, how to fix it, and to make sure it never happens again."

The wound was all the more painful because of the great expectations for Hubble. With a bevy of exquisitely sensitive instruments designed to observe in both visible light and ultraviolet, and an orbit 380 miles above the distortions imposed by Earth's atmosphere, Hubble was supposed to detect objects 50 times fainter than those that can be seen with Earth-bound telescopes. It was to answer some of the most fundamental questions in science: How big is the universe? When did it begin? Are there other worlds like ours? What is the mass of a black hole? What supplies the titanic energy of quasars?

Unless Hubble's problems can be overcome, at least some of these questions will go unanswered.

The trouble with Hubble began long before its launch on the shuttle *Discovery* on April 24. First proposed as an American project by Princeton astronomer Lyman Spitzer in 1946, the project has been beset by delays, management snafus, and cost overruns.

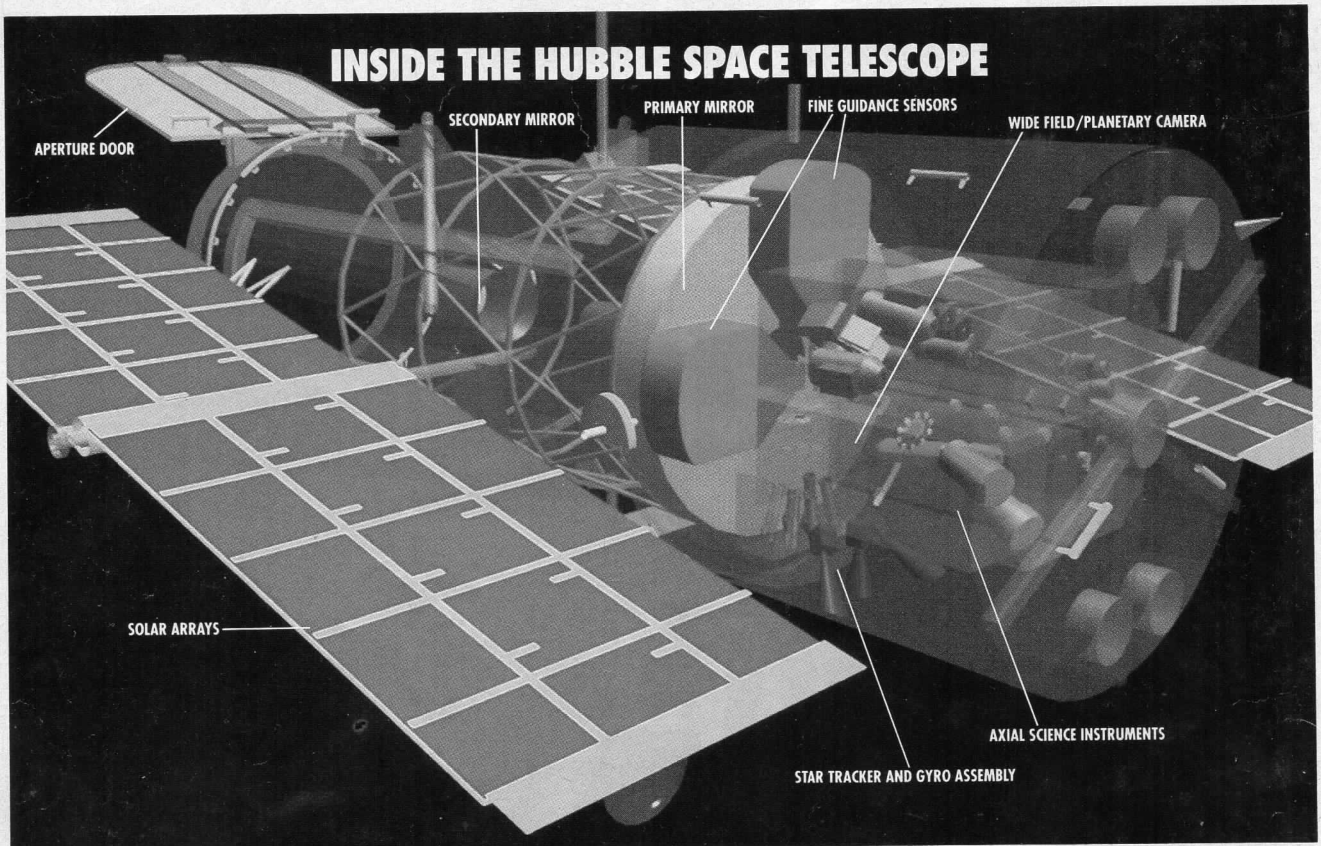
The primary mirror took a punishing five years to grind and polish, and when it was finished in 1981 had cost some $3 million more than was budgeted. Various glitches advanced the original 1983 launch date to the fall of 1986. Then came the fatal *Challenger* accident, and all shuttle launches were suspended for almost three years. (Hubble needs a shuttle to be lofted into orbit. It is 42.5 feet long, about the size of a Greyhound bus, and weighs 127.5 tons. It barely fits into the shuttle's huge cargo bay, with just a measly inch of clearance.) After shuttle flights resumed, Hubble was scheduled to go in June 1989, then slipped to February 1990 and then to April. Finally, on April 24, 1990, the most sophisticated astronomical instrument ever built left Earth's surface for a 15-year mission that would bring a new era in our understanding of the cosmos.

But the troubles were not over. They continued with the deployment of the telescope, a day after the launch. The first operation after Hubble had cleared the shuttle bay, but while it was still tethered to the shuttle, was to open its two antennas, uncoil the solar array masts, and unfurl the twin solar panels. Both operations ran into problems.

The antennas are four-foot dishes on 10-foot masts. When ground-based controllers commanded one of the dishes to swivel, it was blocked—before it could complete its travel—by a loop of cable.

The on-board computer immediately "safed" the telescope; it shut the telescope down rather than permit the antenna dish to strain against the cable.

"The telescope is like a hedgehog—a very sophisticated one," says Stephen Maran, a senior staff scientist at NASA's Goddard Space Flight Center in Greenbelt, Md., and one of the co-investigators on Hubble. "If anything goes wrong, it rolls up in a ball. But there is a whole hierarchy of safe modes, from benign ones to very serious ones. In a benign mode you lose the research you were doing, but you don't close the door of the telescope and shut down the power on everything you can think of." In some situations the computer will change the pointing of the telescope to get the solar arrays to face the sun as much as possible. Then it has to close the telescope door to keep direct sunlight from damaging the instruments. The telescope has safed itself at least half a dozen times, Maran says, in a variety of ways.



Hubble uses a Ritchey-Chretien variation of the Cassegrain telescope design. Incoming light hits a large, concave primary mirror, reflects back to a small convex mirror, which focuses the light back through an aperture in the main mirror to a bevy of instruments. Both mirrors have hyperbolic shapes.

As a result of that first glitch, the antenna dish cannot swivel through all of the arc originally planned, and the time during each orbit that Hubble can communicate (via the Tracking and Data Relay Satellite System) has been reduced by a small but non-trivial amount. "We just had to rewrite the software," Maran says.

Unfurling the solar arrays also triggered a "safe" because of an event that seemed even more threatening. The arrays, made of 1/32-inch-thick Mylar film, each eight feet wide and 39 feet long, are propelled into their open state by the uncoiling of a helical metal tape. But the computer detected a tension in one array that was higher than the permitted limit and stopped the procedure.

"That was serious," says Maran. "If the panels don't unfurl, you have to have an EVA [extra-vehicular activity] right away. The battery is dropping rapidly, and you've got to get the solar arrays working to charge it quickly, or hook it up to an umbilical. If the battery goes dead for a couple of hours, there is equipment on board Hubble that will fail, because it gets too cold."

In fact, two of the *Discovery* astronauts started suiting up and rebreathing oxygen. But when the crew looked out a shuttle window, they could see no sign of the extreme stress in the panel the computer had signaled. They decided to override the computer and continue the operation, which was successful.

Other problems arose during Hubble's first days and weeks in orbit. Astronomers and engineers puzzled over the telescope's apparent confusion over just which stars to aim at. The fault lay in devices called fixed-head star trackers, three little telescopes in the mid-section that are responsible for first approximations to precise aiming. (By contrast, the three fine guidance sensors are capable of locking on to a star that subtends an angle of only 0.007 arc second—equivalent to the diameter of a

HUBBLE'S TROUBLED PAST

1923—German space writer Hermann Oberth speculates for the first time on the possible value of placing an astronomical telescope in Earth orbit. But the idea lay dormant until the rapid development of rocketry in World War II.

1946—Princeton astronomer Lyman Spitzer writes a study titled "Astronomical Advantages of an Extraterrestrial Observatory," noting that only a telescope above Earth's atmosphere can record ultraviolet radiation from heavenly bodies.

1962—A group of scientists organized for NASA by the National Academy of Sciences to study the future of space science recommends the development of a large space telescope as a long-range goal of the nation's space science activities.

1973—NASA selects a group of scientists to consider both the basic design of the telescope and the instruments it will have.

1974-78—The space telescope program is in danger of being postponed indefinitely or being canceled altogether as the result of repeated Congressional and executive budget reviews.

1977—Congress finally approves NASA's recommendations and authorizes the Large Space Telescope. Perkin-Elmer is chosen to build the optical assembly and Lockheed Missiles & Space Co. is chosen to build the support structures and assemble the components of the complete satellite. Launch is scheduled for 1983.

1983—Science instruments are delivered to NASA for testing, but completion of the observatory has fallen behind schedule. The program is renamed the Hubble Space Telescope after Edwin P. Hubble, discoverer of the expansion of the universe.

1985—Assembly of the spacecraft is completed, and launch is rescheduled for 1986. Technical problems cause postponements.

1986—The shuttle *Challenger* explodes, killing its crew of seven astronauts. Without shuttle flights, Hubble is grounded indefinitely.

1989-90—The Hubble launch slips from June 1989 to April 1990.

April 24—Hubble is launched aboard *Discovery*.

April 25—The telescope encounters problems with the deployment of its solar panels and antennas. Soon other problems—with vibration and pointing stability—emerge.

Mid-June—Hubble scientists learn that the telescope's optics do not focus properly.

dime in a window of the John Hancock Building in Boston as seen from the top of the Washington Monument.)

"The fixed-head star trackers were not working well," says Maran. "They were homing in on the wrong stars. They depended for orientation on a star catalog that had been assembled by astronomers, and it turned out that the catalog had mistakes that needed to be corrected. Also, all three were supposed to have square fields of view, but one of them was delivered with a round field of view, accompanied by an apologetic note from the manufacturer. But the note got lost in the system over the years. So this star tracker was missing stars in the corner of the field because it had no corners."

These errors, and the fact that the star trackers are more sensitive (and thus more easily confused) than they were supposed to be, are being compensated for by changes in the data base of the ground system.

More grievous is a problem that was still plaguing Hubble in late July: vibration. Every hour and a half in its whirl around the globe, the satellite crosses the terminator—the boundary between night and sunlit day. The temperature change from bitter cold to warmth happens in a span of just 90 seconds; this "snap" starts the solar panels jiggling, perhaps beginning in the helical metal tapes; and then the whole telescope begins to tremble.

"That can cause you to lose pointing control," says Maran, "and you certainly can't keep a star in a tiny slit. This is the first problem that made people in authority on the space telescope project really worried."

Jean Olivier, the deputy project manager for Hubble and the mission's chief engineer, made plain what the worry was. Unless the vibration problem is solved, he said, "we do not have a space telescope."

Hubble's designers anticipated some vibration as being inevitable, and incorporated compensation for it: a closed loop system with gyroscopes and inertia wheels. But the amplitude and frequency of the thermally induced vibration amount to more than the present control system can cope with. The hope is that new computer software being written by Lockheed (builder of the spacecraft itself) will reduce the vibration by at least a factor of 60—perhaps as much as 100—and make it possible for the telescope to do useful work.

Telemetering new software up to Hubble is not without risks; there is concern lest damaging errors be introduced. "It's like changing a spark plug while driving down the road," says Olivier. "You've got to be careful."

All of these troubles—the vibration, the pointing confusion, the problems with the antennas and solar array—were but premonitory rumbles compared with the earthquake that rattled the space establishment: the discovery that Hubble's vaunted vision was so blurred the mission would not be able to realize more than a fraction of its scientific goals. It was as if an eagle had turned into a bat.

The discovery came in June, after the telescope had finished its coarse-focusing phase and was entering the critical fine-focus phase. Ground controllers took a series of six images of the bright star Iota Carina with the wide field/planetary camera, or WFPC. This visible light camera operates in two modes: a wide-field mode for imaging galaxies and quasars, including those billions of light-years from Earth; and a planetary mode for imaging the entire face of a solar system planet (except Mercury, which is too close to the sun) in a single exposure.

For each of the six exposures, made in the wide field mode, controllers commanded the 12-inch convex secondary mirror to move to a different position along the optical axis—nearer or farther from the primary mirror. One of these images should have shown a dramatically improved focus. But to the dismay of controllers and astronomers alike, the image could not be sharpened, no matter how the mirror was moved.

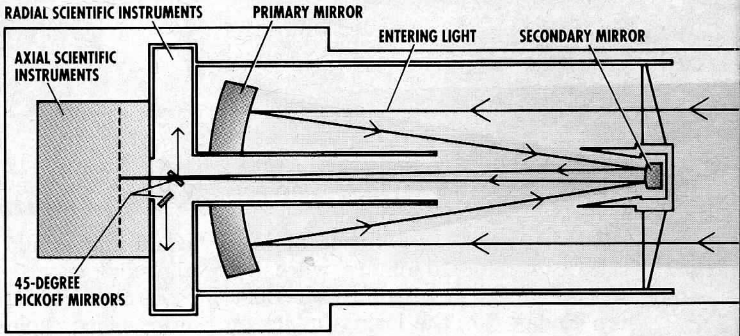
Steve Maran recalls being alerted on the morning of June 26 to devote all day and all night to studying "what an image quality this bad would mean for our science." The next day NASA released the bad news.

The nature of the flaw was immediately apparent from the blurry images. Star pictures that should have been points were instead surrounded by a fuzzy halo, characteristic of the optical defect called spherical aberration. With it, the light rays reflecting from a mirror (or passing through a lens) do not all focus at the same point. Parabolic mirrors are supposed to eliminate spherical aberration; both of Hubble's mirrors are hyperboloidal, a shape that avoids both spherical aberration and another aberration called coma off-axis.

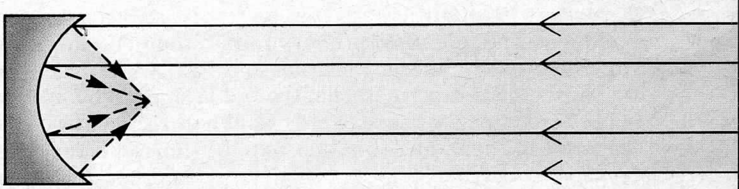
NASA engineers created computer simulations of images that would have resulted if Hubble's mirror system had different degrees of distortion in its curvature. When they ran one that corresponded to the spherical aberration resulting from a deviation of only one-half a wavelength of light—about one-fiftieth the width of a human hair—it closely matched the actual Hubble pictures. From further computer analyses of the faulty images, it seems almost certain that the flaw is in the big primary mirror, not the small one, and not in both.

James Westphal of the California Institute of Technology and the principal investigator on the WFPC called the flaw a "textbook, classic" example of spherical aberration. It is so symmetrical that NASA experts believe it must

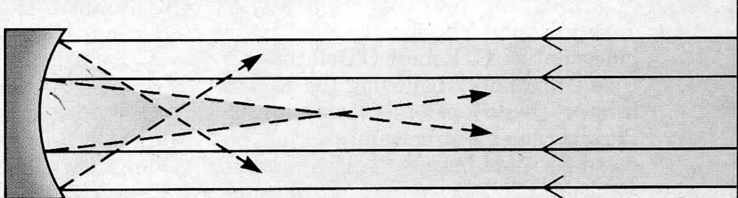
HOW HUBBLE SHOULD WORK



TELESCOPE'S OPTICAL PATH



CORRECT FOCUS OF HYPERBOLOIDAL MIRROR: ALL RAYS FOCUS AT ONE POINT



SPHERICAL ABERRATION: RAYS FOCUS AT DIFFERENT POINTS

DANA BERRY, SPACE TELESCOPE SCIENCE INSTITUTE have been ground in, and not a design error.

Testifying before Sen. Gore's subcommittee, Lennard Fisk, NASA's chief scientist, said that the primary mirror seemed to have been as smoothly polished as specifications called for—no bumps or pits taller than a half-millionth of an inch. Instead, he said, there seemed to be a systematic, symmetrical error in the mirror's curvature. "In other words," he said, "it appears to be perfectly wrong."

"We suspect," Olivier said on June 27, "that the methods used to measure the figure [curvature] of the mirror during manufacture, which are very complex, resulted in the mirror being very precisely made, but to the wrong figure."

The blow to the Hubble team was particularly stunning because, as Maran says, "It was the last thing in the world anyone thought would be defective.

How could such an error go undetected?

The whole question is an exceedingly complex one, because of the exotica of mirror testing, an art more arcane than necromancy. Some experts have lambasted NASA for not doing an "end-to-end" or "all-up" test, in which both large and small mirrors would have been tested as an ensemble. NASA's Olivier responded that the agency had considered but rejected such a test, which he said would have cost hundreds of millions of dollars because a special facility would have had to be built. Other experts countered that a test could have been performed for only $10 million.

The irritated sensibilities of lawmakers and astronomers were not soothed by the revelation that Eastman Kodak Co., the losing bidder on the Hubble telescope, had included in its bid a $10 million test that would have detected the flaw. Moreover, the Kodak proposal called for another company, Itek Optical Systems, to build a second, identical primary mirror. Having two different mirrors and two different testing methods, the bid said, would ensure the accuracy of at least one of them, and that one would be used on Hubble.

In fact, NASA ordered a backup mirror from Eastman Kodak while awarding the telescope contract to Perkin-Elmer. The former chief Hubble scientist, C. Robert O'Dell (now of Rice University), believing the Kodak mirror to be optically superior to Perkin-Elmer's, urged its use, but he was overruled because NASA administrators felt it would poison the project to choose the losing bidder's product over that of the prime contractor. That backup mirror now resides in a wooden crate in Danbury, Conn.

What makes the story even more complicated is the role of the military, spy satellites, and a rumored high-level tug of war between NASA and the Pentagon. It is well-known that spy satellites, also built by Perkin-Elmer, use a telescope similar to Hubble's, with the difference being that theirs is pointed down instead of up. Those telescopes are routinely tested end-to-end at ground-based facilities.

William Burrows, an authority on spy satellites and author of the book *Deep Black—Space Espionage and National Security*, says "It mystifies me why the Hubble telescope wasn't tested end-to-end. It was assembled by Lockheed in the same building used to assemble the spy satellites. It could and should have been tested in the same way they are."

"It appears to be perfectly wrong"

Because of the shroud of secrecy over space espionage, the facts may never be wholly known. But there are reports that the Air Force offered NASA the use of such a test facility some 10 years ago, but was refused, possibly because the military wished to impose too stringent security.

NASA has appointed a commission chaired by Jet Propulsion Laboratory director Lew Allen to investigate the mirror error. It includes both NASA and non-NASA experts, such as Roger Angel, head of the mirror laboratory at the University of Arizona's Stewart Observatory. Their task will involve following a lengthy paper trail of records both from the mirror maker, Perkin-Elmer (now Hughes Danbury Optical Systems), and from NASA's Marshall Space Flight Center. The commission's labors will probably not be completed and a report rendered until October.

Allen has promised that his review panel would disclose not only how the mirror fiasco came about but also who was responsible. "We know the most likely outcome of our investigation will be a result that is very embarrassing to someone or some group." The question is whether the fault lies with the contractors, NASA, or both.

Wherever the buck stops, the mirror's imperfection has led to a hurried reassessment of what science Hubble is still capable of. "We were expecting to have seventy percent of the incoming light focused within a circle whose diameter is a tenth of an arc second," says Maran. "We designed our scientific instruments around that specification and the whole science program. What we're getting now is about ten percent going into that circle and seventy percent into a halo of about 0.7 arc second.

Most severely affected are those programs—and instruments—involved in the imaging of the faintest objects and those demanding the highest degree of spatial resolution —the ability to discriminate between two close-together stars.

Worst off is the WFPC. Edward Weiler, Hubble program scientist at NASA headquarters, stated dejectedly that the instrument—meant to be Hubble's workhorse—would be so degraded that it might simply be turned off, and its heavy share of observing time—some 40 percent—allocated to other instruments that suffered less impairment.

The spectrographs, which don't form images, are less affected. But NASA spokesmen, in an initial rush to take some of the curse off the bad news, may have downplayed the losses that these instruments too will endure.

"NASA has said that our own instrument, the Goddard High-Resolution Spectrograph, will be least affected," Maran says, "and that we can do about seventy-five percent of the science we intended. What that doesn't tell you is that because we won't be able to get all the light from a star it will take much longer to do it, and it won't be done as well."

Can Hubble be fixed? The answer is a conditional yes.

The working plan for repairing Hubble's misty vision is not to fix the telescope as such, but to put corrective spectacles in the form of small curved mirrors on new instruments that will replace the present ones. Because the aberration does seem to be a straightforward one, NASA optical scientists and engineers should be able to deduce the right "prescription" from the images obtained by the wide-field and

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The trouble with Hubble

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faint-object cameras. These corrective mirrors would be about the size of a nickel.

James H. Trainor, associate director of the Goddard Space Flight Center, says the wide-field camera would be the first to get this treatment. "It was scheduled to be replaced by a second-generation instrument anyway in 1993." That job is to be performed by a shuttle astronaut during an extra-vehicular activity.

High-risk fixes

Two other scenarios for fixing the focus were briefly considered and quickly discarded. One was to retrieve Hubble, bring it back to Earth, and replace the mirror with a waiting backup, presumably free from flaws. That would have posed enormous mechanical risks and enormous costs. The other was to apply a kind of doughnut to the telescope, just as a camera lens is "stopped down" to improve its sharpness. The gain would have been small, and the risk of contaminating the telescope great.

What is inevitable is that coping with Hubble's problems is going to consume more money than was budgeted—lots of it. One estimate is at least $25 million a year. "There's only one place that can come from," says Trainor, and that's the funding for AXAF, the Advanced X-Ray Astrophysics Facility, and SIRTF, the Space Infrared Telescope Facility. Both belong to the series NASA calls Great Observatories. AXAF was scheduled for launch in 1996 and SIRTF by 2000, but Trainor fears they, and maybe other NASA projects, will be delayed by the ripple effect of Hubble troubles. Grandiose schemes like the space station and the Moon-Mars missions are especially vulnerable.

Edwin Hubble died in 1953, after a life devoted to the pursuit of the unknown through astronomy. What might his reaction have been to the troubles of the great telescope bearing his name? To use his own words:

"The search will continue. The urge is older than history. It is not satisfied, and it will not be suppressed."

On Aug. 9, NASA announced that the flaw in Hubble's primary mirror was apparently caused by a spacing error of one millimeter in part of the complex optical system used to gauge precisely the curvature of the mirror during its final grinding and polishing. The guilty part is called a null corrector; a focusing lens is a millimeter too far from one of the corrector's mirrors. NASA stated that "a discrepancy of this magnitude" could account for Hubble's fuzzy focus. PS