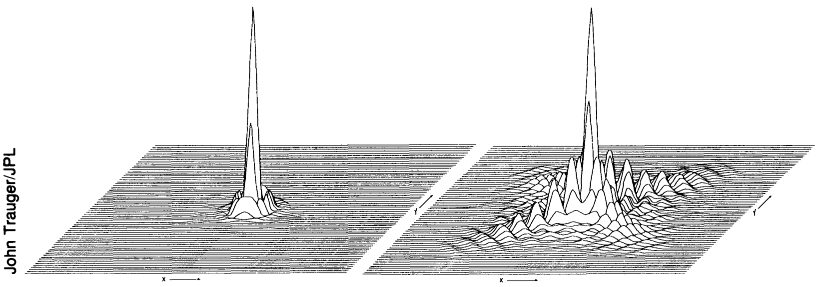
Astronomers Survey Hubble Damage

Seldom has so tiny an error caused so vast a turmoil—but in a $1.6-billion telescope, micrometers loom large. Researchers are now conducting triage on the observing program

TO THE ASTRONOMERS it feels like an earthquake—a sudden shock that has ripped through the Hubble Space Telescope project and left most of their observing programs dead or gravely injured. Vague rumors that something was amiss started circulating on 20 May, the day the $1.6-billion telescope produced its blurry First Light image. They turned out to be all too true in late June: a subtle error in the shape of one of Hubble's two mirrors amounting to just one one-hundredth the width of a human hair has left it with an optical defect known as spherical aberration. Every image of every star has become a point surrounded by a fuzzy halo, and those long-awaited, beautifully crisp images of the heavens are not to be.



John Trauger/JPL

Wish meets reality. *A computer plot of light intensity versus position shows what Hubble ought to see when it looks at a star (left), and what it does see (right).*

"We feel 95% devastated," says Lick Observatory astronomer Sandra Faber, a science team member for the telescope's Wide Field/Planetary Camera (WF/PC). The most heavily subscribed of Hubble's instruments, WF/PC has been impacted more than any other. Other Hubble scientists are somewhat better off, but only somewhat. Their preliminary efforts at triage indicate that no more than 20 to 30% of their observing programs can be counted among the walking wounded. Another 20 to 30% are going to require intensive care. And as many as 40% may have to be given up for lost. "This is a major loss," says Faber, "a major disaster."

Still, old Hubble hands long ago learned to cultivate a certain stoicism about such afflictions. After all, the telescope has already been delayed 7 years beyond its original launch date and has overrun its original cost estimates by a factor of 4 or 5. "No one likes to be kicked in the head," says University of Colorado astronomer John Brandt, principal investigator for the telescope's High Resolution Spectrograph. "But we've had kicks in the head before on this project, and you're naïve if you thought they wouldn't come again."

As bad as it is, moreover, the one saving grace about this particular disaster is that it's fixable—eventually. A second generation of Hubble instruments is already under development, and the scientists are now reasonably confident that corrective optics can be inserted to undo the damage entirely. Assuming that NASA is actually able to keep the shuttles flying on schedule—not exactly an inspiring proposition these days (see p. 115)—and assuming that the telescope is not disabled in the meantime by an electrical failure or some other catastrophe, the astronauts could install the second generation WF/PC as early as 1993. Two more instruments—an infrared camera and an imaging spectrograph—could follow in 1996.

Damage Assessment

Instrument	Purpose	How Affected
Wide field/ planetary camera	High resolution images in visible light; wide field of view; Hubble's workhorse instrument	Sharply degraded
Faint object camera	Highest resolution images of the faintest objects in visible and UV; narrow field of view	Sharply degraded in visible; moderately degraded in UV
Faint object spectrograph	Spectra and polarizations of very faint objects in visible and UV	Faintest objects lost; rest moderately degraded
High resolution spectrograph	Very high spectral resolution in UV only	Highest resolution lost on faintest objects; rest moderately degraded
High speed photometer	Very accurate light intensities measured 100 times per second	Faint objects moderately degraded
Fine guidance sensors	Accurate pointing of telescope; very precise positions of stars	Probably unaffected

And so, like the survivors of many a real earthquake, the Hubble scientists are sorting through the rubble and planning how to rebuild. Some are even willing to count a few blessings along the way. "We are fortunate," says Peter Stockman, deputy director of the Space Telescope Science Institute in Baltimore. Hubble is safely in orbit, he points out. All of its electronic subsystems and all six of its scientific instruments appear to be working perfectly. And its early pointing and stability glitches are fixed or well on their way to being fixed. "There could have been other types of problems with the mirrors or the vehicle that would have been much more difficult to solve," he says.

Be that as it may, Stockman expects the case-by-case analysis of the observing programs to last until September or October. By then the observation schedule will have been revised, with priority given to those observations that are still doable.

Already, says Stockman, it's clear that the original rule of thumb—that the telescope's imagery would be devastated while the non-imaging experiments would be largely unaffected—was too simple. It turns out that many observers can compensate for the starlight that leaks away into the aberrant halo by simply taking longer exposures. So a better way to sort things out may be to ask about observing time: how much more will a given observer need?

Using that measure, says Stockman, you can identify a category of modestly affected observations that should be able to proceed more or less as currently planned. Perhaps the most certain candidate for membership in this group is the science being planned for

Hubble's Fine Guidance Sensors. Primarily designed to keep the telescope locked on target within 0.007 arc second—equivalent to piercing a dime in Boston with a laser based in Washington, D.C.—the three identical sensors are also able to do ultra-high precision astrometry: the measurement of where stars are located in the sky. And as luck would have it, says astrometry principal investigator William Jefferies of the University of Texas in Austin, those measurements should proceed without a hitch. Assuming that the spherical aberration is as textbook perfect as it now appears to be, it should have absolutely no effect on the sensors. Indeed, he says, "They're now guiding the telescope quite successfully."

Jefferies expects that he and his astrometry team will spend the bulk of their time on the prosaic, but fundamental, job of refining the interstellar distance scale. The only direct way to measure a star's distance, he explains, is to measure its parallax: the tiny, yearlong oscillation in its apparent position in the sky as Earth moves around the sun. Though these are not the kinds of results most people have in mind when they think of the Hubble's vaunted capabilities, such measurements are the ultimate standards by which we estimate the distance of the quasars and the age of the universe, says Jefferies, and Hubble still promises to make them ten times more accurately than they have ever been made from the ground. At the same time, he says, Hubble may also find that certain stars oscillate for another reason: not because they are showing parallax, but because they are being tugged back and forth by the gravity of a large planet.

Another prime example of a low-impact program is the Medium Deep Survey, an imaging effort that has been designated by the science institute as one of the telescope's three highest priorities. (The other two, discussed below, are a survey of quasar spectra and a better determination of the age of the universe.) The original idea of the survey was to take advantage of Hubble's ability to make several observations at once: whenever the telescope was busy taking spectra or photometric readings of some object in the foreground, ground controllers would simply open the WF/PC shutter and take a long exposure of whatever lay in the background. At a minimum, says survey principal investigator Richard Griffiths of the Science Institute, the resulting WF/PC images would have contained myriads of very faint and very distant galaxies and quasars, and would have given observers an unparalleled view into the early epochs of the universe. But with any luck, he says, the images might also have revealed whole new classes of astronomical phenomena that no one had even thought of.

Given the spherical aberration, however, imaging those distant galaxies and quasars now looks very tough. Too much of their scarce light is being lost into that fuzzy halo. So instead, says Griffiths, "we'll probably emphasize the part of the program that's not doable from the ground"—namely, observations in ultraviolet light, which is absorbed by Earth's atmosphere. White dwarf stars, cataclysmic binary stars, and quasar-like "active" galactic nuclei will all be fair game.

"I'd be lying if I said I wasn't disappointed" at losing the most distant galaxies, says Griffiths. On the other hand, the ultraviolet region promises to be a particularly good hunting ground for new phenomena, he says, precisely because it is so rich in spectral lines and because it remains almost completely unexplored. The only reason he and his colleagues had not emphasized these ultraviolet observations before was because they had played it safe on their original proposal: "We didn't know what we were going to find." Now they should get a chance to learn.

Back at the Science Institute, meanwhile, Stockman estimates that another 20 to 30% of Hubble's programs will fall into the catagory of "moderate" impact. "They can achieve the same ends," he says, "but only with about two to four times the amount of observing time they had planned." Many of the telescope's spectroscopic and photometric observations fall into this group, with perhaps the prime example being the quasar absorption line survey, the second of the Science Institute's three highest priorities.

The original idea here was to take advantage of the fact that the quasars are like far-off lighthouses shining to us through a cosmic haze of galaxies and intergalactic gas clouds. Many of these intervening lumps may well be newborn galaxies, and many others may well be galaxies in the process of being born. Under normal circumstances these objects are much too far away and too faint to see directly, which is why galaxy formation remains one of the murkiest areas in cosmology. But in principle, they should stamp each quasar's spectrum with the telltale ultraviolet absorption lines of hydrogen and other gases, with each line looking like a sharp little notch in a plot of the quasar's intensity versus wavelength. Indeed, ground-based quasar spectra show such absorption lines by the hundreds: each one represents a gas clump or galaxy so far away that its ultraviolet Lyman-alpha line of hydrogen has been redshifted into visible

A Question of Time

Of all the issues NASA officials and Hubble Space Telescope astronomers have to grapple with as they sort through the implications of the instrument's abberrant optics, none is likely to be more sensitive than that of the Guaranteed Time Observers (GTOs). These are the astronomers who have collectively been given hundreds of hours of free viewing time on the telescope—and the right to take the first crack at their favorite celestial targets—in return for spending the past 13 years helping NASA develop Hubble's six scientific instruments. The GTOs entered into this bargain with every intention of skimming the scientific cream in return for their labors. And since it is not their fault that many of their planned observations are now facing years of delay, how is NASA going to compensate them?

"I don't know," admits Edward Weiler, Hubble program scientist at NASA headquarters and the man who finds the question landing squarely on his desktop. Just after the 4 July holiday he formed a committee of GTOs and other scientists to help him decide. But the answers probably won't come easily.

Suppose, for example, that a GTO had planned an observation that is impossible to carry out with the Space Telescope optics the way they are. It would be easy enough to give that GTO some extra time for the project several years down the line, says Weiler, once space shuttle astronauts have equipped the telescope with second-generation instruments that carry corrective optics.

But what do you do about the GTO's target in the meantime? Do you forbid anyone else to look at it to make sure the GTO doesn't get scooped? One problem with that approach: If the GTO chose it in the first place, it's likely to be one of the juiciest and most scientifically rewarding objects in the sky. So do you really want to lock it up for 3 years, or even 6 years? Suppose some non-GTO astronomer comes along and says, "Hey, I've got this neat new computer algorithm that can clean things up and give me an answer!" Doesn't he or she deserve a chance to try it? But then, wouldn't that be a betrayal of the GTO? "The deeper we dig," sighs Weiler, "the more worms we're going to find." ■ M.M.W.

wavelengths that can make it through the atmosphere. With Hubble, the quasar survey could have extended those spectra into the ultraviolet to show closer and more recent galaxies, eventually tracking their evolution right up to the present day. Moreover, it could have done so with hundreds of quasars, providing a sampling of galactic evolution all over the universe.

Hubble can still do most of that, says survey principal investigator John Bahcall of the Institute for Advanced Study in Princeton—but only at a price. The problem, he explains, is that the spherical aberration will produce exactly the same fuzziness in the spectral lines that it does in the images, causing the lines to run together into a similar blurry mess. It is true that either one of the telescope's two spectrographs can sharpen the lines by letting in light through a smaller opening—in effect, chopping off the aberrant halo. But a smaller opening also means less light. And that means, in turn, that the survey astronomers will have to compensate with a longer exposure time for each quasar: "more than a factor of 2," says Bahcall.

The additional time required for such observations will presumably be freed up by the deletion of the severely impacted programs—those that would require a prohibitive amount of extra time to achieve their goals, if they could still be achieved at all. In general, these are the programs that would require the very highest spatial resolution, or that would attempt to image the very faintest objects; Stockman estimates that they account for roughly 30 to 40% of the telescope's previously planned observations.

"There is a whole category of programs designed to look for evidence of massive black holes in the cores of galaxies," says Richard Harms of the Applied Research Corporation in Landover, Maryland, principal investigator for the telescope's Faint Object Spectrograph. "Ellipticals, spirals—all kinds. But you need that spatial resolution to bore right in. So my guess is that those programs are dead."

Colorado's Brandt likewise fears that he will have to delay his own favorite program: a study of the deuterium-hydrogen isotope ratio in comets. Did the comets, which are mostly ice, originate in our own solar system or are they migrants from interstellar space? Are they the source of Earth's oceans? Hubble could have answered all these questions, says Brandt. But for now, it probably can't deliver the needed spectral resolution.

Perhaps the most dramatic casualty of the aberration will be the third of Hubble's three key projects: a better determination of the age and size of the universe. Once again, the issue is distance, says Caltech's Jeremy Mould, principal investigator on the project. How far away are the galaxies? Knowing that, and knowing how fast the galaxies are receding from us, which can be directly measured from their redshift, it would be a simple matter to work backward and figure out when everything flew outward from a point—the Big Bang.

The problem, says Mould, is that once you get beyond the Andromeda galaxy and a few other nearest neighbors, those distances become uncertain by a factor of 2. There simply are no decent yardsticks out that far. And that was what Hubble was going to change, by reducing the uncertainty to 10%.

The idea was to train the telescope on the close-packed galaxies of the Virgo cluster, which lies some 30 to 75 million light-years away, and use ultrahigh resolution imagery of the crowded star fields to pick out the Cepheid variables—a class of pulsating stars that have long served as standard distance indicators in our own cosmic neighborhood. A Cepheid's pulsation period, which is easy to measure if you can just see it, turns out to be very strongly correlated with its true brightness. Thus, by carefully measuring the apparent brightness of each Cepheid in Virgo, and then comparing that figure with the true brightness as derived from the period, the telescope could accurately determine the cluster's true distance. From that would follow a much improved value for the Hubble parameter, which relates a given galaxy's redshift to its distance. And from there it would be just one short step to the true age of the universe.

Except that none of this is going to happen anytime soon, says Mould. "Those star fields are very crowded," he says—just the kind of situation where the aberrant halo will make for maximum confusion. "It's possible we will be able to do some preliminary calibration, but the main thrust of the program *has* to wait for WF/PC II."

As the Hubble scientists try to sort all this out, however, they are still facing two major uncertainties. First, how good (or how bad) will the telescope's images actually be? The original design specification for the optical system called for at least 70% of the light from each star to go into a tightly defined spot just 0.1 arc second across, or about ten times better than the resolution typically available on the ground. But even though most of that light is now leaking out into the aberrant halo, about 15% of it does go into a sharp, 0.1–arc second "core." So there is still some high-resolution information available. And that means that images of planets, nearby galaxies, and other relatively bright objects may still be scientifically useful. An ad hoc committee is now drawing up a list of target objects to test that possibility.

The second uncertainty is computer processing: how much of the lost image quality can it really restore? In principle, the answer is "everything." Almost all the information is still there in the image, after all; it's just improperly arranged. So in theory a computer ought to be able to sort it out quite handily. Indeed, WF/PC principal investigator James Westphal of Caltech has already gotten at least half a dozen offers of help from radio astronomers, who do this kind of "image deconvolution" routinely.

In practice, however, the image processing algorithms require supercomputer-scale number crunching and will be correspondingly expensive to use. Moreover, they will almost certainly not be able to handle images of very faint objects, where there are not many photons to work with. Nor are they likely to have much success with crowded star fields, where the halos overlap into a solid mass. And even with bright objects, the test images that Westphal and his group have processed to date show modest improvement at best.

"They look nice," says WF/PC team member Todd Lauer. "But I'm not sure I'd like to do science with them." That may change as the algorithms are refined, he admits. But until then he's inclined to wait for WF/PC II. ■ M. MITCHELL WALDROP

The Investigators

On 2 July, NASA space science chief Lennard A. Fisk appointed a formal board of investigation to find out how the $1.6-billion Hubble Space Telescope wound up crippled by spherical aberration. The board has already sequestered more than a decade of documents from the telescope's optical subcontractor, Hughes Danbury Optical Systems, and will review every phase of the mirrors' design, manufacture, and testing. The board will be chaired by Lew Allen, director of NASA's Jet Propulsion Laboratory and formerly director of the National Security Agency. The other members:

Charles P. Spoelhof, retired vice president of the Eastman Kodak Company; **George A. Rodney**, NASA associate administrator for safety and mission quality; **John D. Mangus**, head of the Optics Branch, Space Technology Division, at NASA's Goddard Space Flight Center; **Robert Shannon**, astronomer at the Optical Sciences Center, University of Arizona; **Roger Angel**, astronomer at Steward Observatory, University of Arizona.

■ M.M.W.