Space Astronomy: The Next 30 Years

Astronomers see Space Telescope as only the first in a series of orbital observatories; but will Washington see it that way?

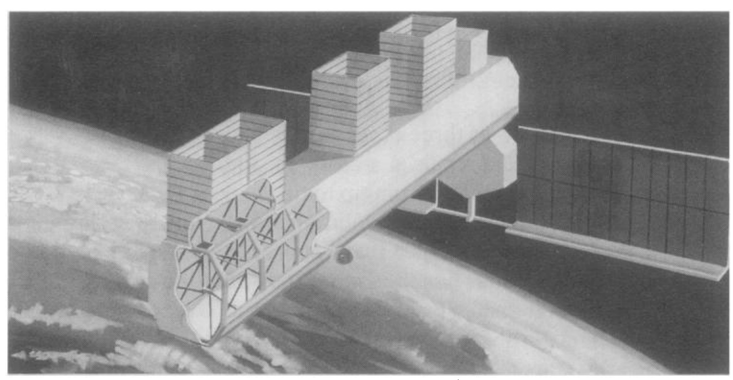
With the 1985 launch of the National Aeronautics and Space Administration's (NASA) Space Telescope still more than 2 years away, people are already hailing it as the instrument of the century, one of the most momentous advances in astronomy since the first telescope of Galileo.

Fair enough. It will be the first large (2.4 meter) optical telescope to operate free of clouds, turbulence, airglow, and the atmosphere's tendency to absorb everything but visible light and radio waves. It will image the planets in Voyager-like detail. It will track the evolution of galaxies over the past 8 billion years, and the evolution of quasars a lot further back than that. It may even determine whether some of those galaxies—including our own Milky Way—harbor massive black holes in their centers (*Science*, 21 May, p. 838).

But Space Telescope is not the final word in space technology, nor will it solve every problem in astronomy. In fact, the National Academy of Science's Astronomy Survey Committee (the "Field" Committee), which recently released its 10-year report on astronomy's needs for the future, has recommended at least a half dozen new spaceborne instruments for development in the 1980's alone (*Science*, 16 April, p. 282). Some of these facilities are needed for specialized purposes such as solar physics. Others would cover x-ray or radio frequencies that Space Telescope cannot reach. Still others would go far beyond Space Telescope in resolution, sensitivity, or light-gathering power.

"It's a problem of perception," says one NASA scientist. "People outside the community don't see Space Telescope as the first piece in a grander program for space science." Unfortunately, he says, the kind of rhetorical overkill they are hearing now comes all too easily when scientists and administrators are trying to justify expensive programs. But in the long run it undermines the larger goal. If scientists do not start putting Space Telescope in a little more perspective, for example, Congress and the White House might just respond to every future request by saying, in effect, "We already *gave* you a space telescope!"

Some of that perspective was provided last October in Danbury, Connecticut, as astrophysicists, industrial specialists, and NASA officials met to take a look at what space astronomy might accomplish over the next 30 years.* It was apparent at the meeting that the advent of a working space shuttle has begun to inspire some marvelously imaginative designs. It was also apparent that people are worried. None of the proposed missions will be cheap. And while NASA's astrophysics budget has been doing relatively well in dollar terms, most of that money is going to complete Space Telescope. "New starts are being put off at the rate of 1 year per year," said one bitter x-ray astronomer. The meeting's sessions on "Cutting Costs" and "Selling Science" were well attended.



COSMIC

A cutaway drawing of the first module shows the square mirrors and internal optics.

Marshall Space Flight Center

Meanwhile, Herbert Gursky of Naval Research Laboratory led off the technical discussions with a look at the future of optical astronomy in space.

Astronomers' endless quest for better angular resolution and greater collecting area means that Space Telescope's successors will inevitably grow bigger and bigger, he pointed out. But unfortunately, Space Telescope is already as big as the space shuttle's payload bay can handle. So new approaches are needed.

Perhaps the simplest idea involves the space shuttle's external fuel tank, the huge pod that towers over the orbiter while the shuttle is on the launch pad. The current practice during launch is to drop the tank into the ocean once its fuel is exhausted. However, by cutting back on the shuttle's internal payload, the tank could be taken all the way into orbit. Once there, said Gursky, it could be used as the casing for an 8-meter telescope—more than three times the size of Space Telescope and more than half again the size of the 5-meter Hale telescope on Mount Palomar.

This "Very Large Space Telescope" has been studied at NASA's Marshall Space Flight Center in Huntsville, Alabama. "It would essentially be a scaled-up version of Space Telescope," said Gursky. "But it would be better by a factor of 2 or 3 in angular resolution and a factor of 10 in collecting area."

With that kind of performance the Very Large Space Telescope would be able to see individual stars and star-forming regions in galaxies hundreds of millions of light years away—thereby addressing some fundamental questions of galactic evolution—and might possibly be able to detect planets around nearby stars. Ten times more collecting area would focus ten times as many photons into the detectors, which in turn would mean that faint objects could be studied at roughly three times the distance.

In the long run, however, even that will not be enough, said Gursky. So the Marshall center has also studied a pair of even more ambitious instruments: COSMIC, a space-going optical interferometer, and TAT, the "Thinned Aperture Telescope."

COSMIC's initial module (designed to

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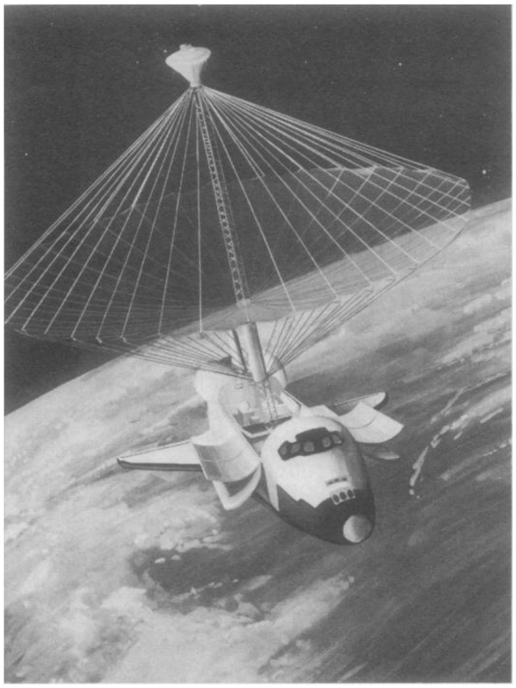

Astronautics and Aeronautics

VLBI antenna in space

fit into the shuttle bay) would consist of four 1.8-meter optical telescopes in a line, all of them pointing in the same direction. The idea is to take the light gathered by each mirror, feed it into an exceptionally accurate optical system, and direct it to a single focus with all the beams in phase. The resulting image would then have a resolution equivalent to that of a single telescope as big as the whole array—in this case, about 16 meters.

The addition of three other modules to COSMIC would result in a cross-shaped array some 36 meters from tip to tip, said Gursky. The theoretical resolution of the complete array would then approach 0.003 arc second, which is more than 30 times better than Space Telescope, and sufficient to observe surface activity on nearby stars ("starspots"), or to resolve the nuclei of active Seyfert galaxies.

On the other hand, said Gursky, COSMIC would be relatively inefficient at gathering light. (Mirrors cover only a small percentage of the array, and most of the light passes through.) The Marshall center has therefore designed a complementary system: TAT, a light bucket some 100 meters across.

TAT would be an annular ring, essentially a vast parabolic mirror with the center cut out. Diffraction effects caused by the missing center would make a mess of the images, said Gursky. But the goal is collecting area, not resolution. "TAT is the basis for doing the deep cosmological issues, when you are looking for every last photon," he said. And the design does allow the shuttle to bring up material for TAT in a reasonable number of launches.

"The challenge in all of these approaches is that you must clearly bring up large amounts of material and do real construction in space," he added. "Even the Very Large Space Telescope will require a complex disassembly of the external tank and reassembly of the telescope, all in zero gravity." Although NASA has given a fairly high priority to a demonstration of such space construction techniques, the agency is still a long way from doing it.

In addition, the technology for building large, lightweight, high-precision mirrors is still in its infancy. The instruments may well have to use mirrors built in segments. And especially in COSMIC, computer-driven "active optics" will be needed to keep everything in precise alignment (*Science*, 16 April, p. 280).

Following Gursky, Thomas G. Phillips of the California Institute of Technology discussed the prospects for space astronomy at submillimeter and infrared wavelengths, 10 to 1000 micrometers. When looking at material in the local environs—that is, within the galaxy—this is tantamount to the study of matter at temperatures between 5 K and 500 K, he said. This range includes both continuum emissions from interstellar dust and line emissions from interstellar molecules such as carbon monoxide. Moreover, it corresponds exactly to conditions within the dark, dense molecular clouds, where stars are forming and where optical telescopes are useless (*Science*, 5 February, p. 647).

"What we're after is detailed maps of the star-forming regions," said Phillips. "We'd like to know what is happening at the center. For example, can we see little preplanetary disks around stars?"

With current ground-based instruments that is out of the question, he said. Their resolution is too poor, and most infrared and submillimeter photons are absorbed by water vapor in the atmosphere. However, things would begin to change with the construction of the Field Committee's priority number four: the Large Deployable Reflector in Space (LDR). The LDR design calls for a 10- to 20-meter segmented mirror in orbit, with active optics controlling the segments to achieve about a 1-arc second resolution at the submillimeter/infrared wavelengths.

"At 1 arc second we could do well with star formation all the way out to the Magellanic clouds," said Phillips. "We could even see molecular clouds in other galaxies." If it were possible to reach 0.1 arc second, he adds, the preplanetary disks would begin to come clear, and it might even be possible to identify planets in other solar systems spectroscopically. But achieving 0.1 arc second at these wavelengths will require something much larger than LDR—most likely, a submillimeter/infrared interferometer, of which LDR could be a part.

Turning to more cosmic questions, said Phillips, LDR could address the question of the missing mass (*Science*, 30 January 1981, p. 470). Astronomers are convinced that there is more to the universe than meets the eye: the outer reaches of spiral galaxies rotate too fast, and in clusters of galaxies the individual members move too fast. The visible stars and dust clouds do not have enough mass to hold everything together by gravity, so something else—the "missing" mass—has to be making up the difference.

Much of the speculation has centered on exotica such as massive neutrinos, magnetic monopoles, and even clouds of black holes. But the missing mass might equally well be in the prosaic form of stars, very cool "brown dwarves" forming a halo around the galaxy. If that is the case, Phillips said, then LDR will do a good job of finding them.

Finally, said Phillips, the LDR could use its light-gathering power to study primeval galaxies in the act of formation, perhaps only a few thousand years after the big bang. It would be uniquely suited for such work, because cosmic expansion is redshifting the ultraviolet and visible spectral lines of the objects into the far infrared.

Moving from Phillips' spectral band into the radio frequencies, Bernard F. Burke of the Massachusetts Institute of Technology described the possibility of building a radio telescope effectively larger than the earth.

The idea is to extend the technique of Very Long Baseline Interferometry (VLBI) into space, he explained. Essentially, VLBI takes tape-recorded signals from widely separated receivers, combines them by computer (using atomic clocks to match phases), and generates a composite image. An informal VLBI network, using existing radio telescopes spread over much of the Northern Hemisphere, has been operating since 1971 and has achieved resolutions in the milliarc seconds, by far the best in any branch of astronomy. Relativistic jets emerging from the cores of certain quasars have been imaged on the scale of just a few light years. Similar jets, on a much smaller scale, have been seen around the bizarre stellar object SS433. The technique has proved so powerful that the Field Committee has recommended construction of a dedicated VLBI network that could work full time.

In addition, says Burke, the network's

resolution could be improved quite dramatically by the addition of an antenna in space. Essentially, the antenna's orbital velocity would allow it to sample different regions of the incoming signal very quickly. (In more technical terms, the antenna's signal would rapidly fill in the Fourier transform of the image of the source. The more complete the transform, the sharper the final image.) This would also allow the VLBI network to monitor the very rapid changes going on in objects such as SS433, and would allow it to expand coverage into the Southern Hemisphere.

How do you get such antennas into space? Burke asked. One attractive opportunity offers itself: both NASA and the Pentagon are interested in demonstrating their ability to deploy large antennas in orbit, and in fact there is talk of trying it later in the decade with a 50-meter dish unfolded from the shuttle payload bay. Even if such an antenna stayed up for only a week, said Burke, it could do useful astronomy. Later, depending on NASA's prosperity and its generosity toward astrophysics, a permanent version could be placed on a space platform.

Finally, at the high-energy end of the spectrum, there is the Field Committee's number one priority for astronomy in the 1980's: AXAF, the Advanced X-ray Astronomy Facility. George W. Clark of the Massachusetts Institute of Technology was at Danbury to tell the story.

Since high-energy photons are strongly absorbed in the atmosphere, he explained, x-ray astronomy is totally dependent on space. Yet, in less than 20 years the field evolved from its first sounding rocket flight to the image forming x-ray telescope on the Einstein Observatory.

"Einstein whetted people's appetite," said Clark. In its 2 years of operation between 1979 and 1980, it obtained spectra and detailed images of thousands of objects, both in this galaxy and elsewhere. "Hundreds of astronomers participated," he said. "In effect, Einstein became a national observatory for x-ray astronomers."

"We now know that million-degree plasmas are the most common sources of x-rays, and that these plasmas are found in objects of every kind," he said. Examples include stellar coronas, pulsars, bursters, supernova remnants. "There are millions of sources, some of which emit most of their energy as x-rays."

The next generation x-ray observatory, AXAF, would be a scaled-up version of Einstein capable of ten times better resolution and 100 times the sensitivity for faint objects, said Clark. Like Space Telescope, it would be launched, serviced, and refurbished by the space shuttle, and would operate as a national observatory for at least 10 years.

Unfortunately, he added, the financially strapped NASA has put off a new start on AXAF again and again. And since the demise of Einstein there are no new data coming in. "X-ray astronomy is dying in the United States for lack of facilities," he said. The only missions now funded are foreign—the European EXOSAT and the German ROSAT, for example—and those are not as advanced as AXAF.

Clark serves in a NASA working group seeking ways to trim the price tag on AXAF to under $500 million. But he is not optimistic.

"There is a question whether NASA's growing drive for a space station [*Science*, 10 September, p. 1018] will crowd out space science already battered by the shuttle," he concluded, voicing a fear common in the space science community.—**M. MITCHELL WALDROP**

Laser Light "Cools" Sodium Atoms to 0.07 K

Slow-moving atoms could lead to ultrasensitive laser spectroscopy, atomic timekeeping, and tests of fundamental physical theories

Researchers at the National Bureau of Standards (NBS) in Gaithersburg, Maryland, have "cooled" a beam of sodium atoms emitted from a hot oven to an effective temperature of 0.07 K by irradiating the beam head-on with a laser beam. By absorbing and reradiating about 30,000 photons, each atom is slowed to a speed of about 40 meters per second (m/sec) during the cooling process. The availability of such slow-moving particles could open the way for investigators to make ultrahigh resolution laser spectroscopic studies of atoms and possibly molecules, to create atomic clocks and frequency standards of unprecedentedly high accuracy, and to carry out supersensitive tests of fundamental physical theories, such as quantum electrodynamics and general relativity.

The fundamental problem for spectroscopists who wish to make high-resolution measurements of atoms or molecules in the gas phase is the motion of the particles. The familiar Doppler effect, for example, gives rise to frequency shifts that broaden an intrinsically narrow line in an absorption spectrum. Each particle sees the frequency of the light altered by an amount proportional to its velocity relative to the light source ($\Delta\nu/\nu = \pm v/c$, where ν is the frequency, v is the particle speed, and c is the speed of light). The shift is positive (blue shift to higher frequencies) if the particle moves toward the light source and is negative (red shift to lower frequencies) if the particle moves away from the source. A gas with a thermal distribution of velocities thus exhibits an absorption spectrum that is the superposition of these frequency-shifted absorption lines.

In the 1970's, spectroscopists devised several techniques for dealing with the Doppler effect [saturation spectroscopy, two-photon absorption, crossed atomic beam and laser beam, and variations of these (*Science*, 13 October 1978, p. 141, and 2 July 1982, p. 9)]. But atomic and molecular motion remains a problem for the ultrahigh resolution spectroscopy that the newest laser technology makes possible. The ultimate limitation is the second-order Doppler effect that is due to the dilation of time in special relativity. The frequency shift, being proportional to the square of the particle velocity ($\Delta\nu/\nu = -v^2/2c^2$), is much smaller than that due to the first-order Doppler effect and is always negative (red shift). A second difficulty stems from the finite time the particles spend in the laser beam because the frequency of a light wave that is not infinitely long is uncertain. The uncertainty is inversely proportional to the time the particle "sees" the light ($\Delta\nu = 1/2\pi\Delta t$). Consider a typical atomic beam with velocity 1000 m/sec that perpendicularly (to eliminate the first-order Doppler effect) intercepts a laser beam 1 centimeter in diameter and frequency 5×10^{14} hertz (orange light). The sec-

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