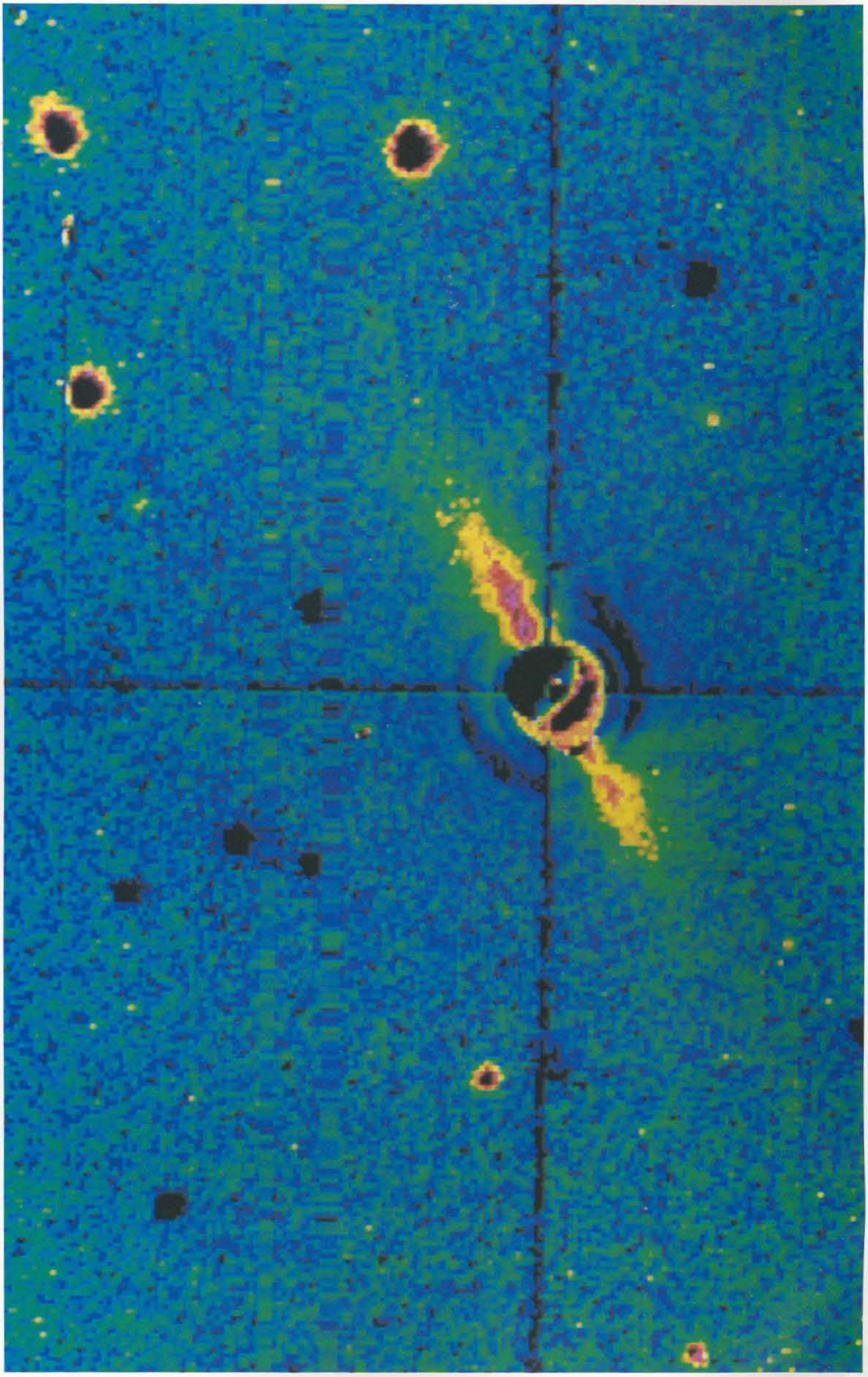


# Prospecting for Planets

*The obvious next step is to go from exploring the planets to exploring the nearby stars and whatever worlds might exist around them.*

**by Richard J. Terrile**

**Evidence of what may be a planetary system orbiting the star Beta Pictoris, about 50 light- years away, shows up in this image made in 1984 by Richard Terrile and Bradford Smith, using the 100-inch telescope at Las Campanas Observatory. The perpendicular lines are caused by fine silk filaments that support an occulting mask. This mask removes most of the star's diffracted light that normally would hide the circumstellar disk from view.**

What will be the next big adventure in space? We have sent men to the moon—about 200,000 nautical miles away. We've landed spacecraft on Mars, about 500 times farther away. And with the Voyager spacecraft we've also visited the outer regions of the solar system—10,000 times farther away than the moon. The obvious next step is to go from exploring the planets to exploring the nearby stars and whatever worlds might exist around them.

Humans have always been curious about the night sky. When man realized the relationship between the sun in the daytime sky and the stars in the night sky, it was a fundamental connection in human thought. We are now at another threshold—where technology has caught up with curiosity, and it's very exciting to be there. We now know enough about the theory of planetary formation and the evolution of stars to indicate that perhaps planetary formation is a common phenomenon—the norm and not the exception. And although the nearest stars are about 10,000 times farther away than the outer planets of our solar system and it would take tens of thousands of years to visit them with a spacecraft, we're at least beginning to understand what it takes to directly image planets around other stars. And we can now build what it takes.

Up until now we've been attempting in other ways to discover whether we're alone in the universe. We are using radio telescopes for a program called SETI, the Search for Extraterrestrial Intelligence. In this program we listen to the other stars to see if any kind of intelligent radio signals are being broadcast from them. And of course we've been broadcasting our own "intelligent" radio signals for about 40 years now—television broadcasts, which have left the ionosphere of Earth and are now expanding at the speed of light in a shell about 40 light-years in radius. Within that shell there are about 800 different star systems, and the broadcast shell is now crossing a new star system about every three days. So every three days there's a new opportunity for somebody out there to say, "Ah, 'The Gale Storm Show.'" It's an intriguing thought. Twenty years ago, when this shell was only half as large, it was crossing a star system about every two weeks. If somebody in one of those star systems had then said, "Aha, there's life on Earth; let's broadcast a reply," and had beamed a strong reply signal, then 20 years after that—today or tomorrow—we might be receiving that reply on our arrays of radio telescopes.

But there will be only a short, finite period of time when the Earth is broadcasting its existence as an intelligent civilization. We're becoming much more efficient in transmitting communication around our planet and are adopting fiber optics, instead of broadcasting all this energy that leaks out past our atmosphere. So, perhaps this isn't the best way to look for life on other planets. The Earth has been around for 4½ billion years and we've only been broadcasting for 40. If others aren't actively signaling their existence but just accidentally broadcasting until their technology gets better, the odds are 1 in 100 million that we'll connect.

Our galaxy, like others, contains about 200

**Jupiter-sized planets among the 200 billion stars of the Milky Way could be very common—perhaps even the rule rather than the exception.**

billion stars. To get an idea of what 200 billion stars might look like, we can make a model of a galaxy on the floor, using grains of salt to represent the stars. (This is an experiment you should try at home. It's safe; it's nontoxic; you don't need to wear goggles or any safety equipment; and you can do it unsupervised as long as you clean up afterwards.) A container of salt that you can buy for 25 cents contains about 5 million grains. It turns out that we would need a carload of salt (200 containers) to make a billion stars on our floor, and in order to get enough to represent all the stars in the galaxy, we would need a whole trainload of salt.

To spread this trainload of salt out to make our model, we'll have to calculate how far away each grain has to be from its neighbors. We know how far away the stars are, and we know how big they are, so we can figure this out easily enough. (In this model, with our Sun a grain of salt, the Earth is about 2 inches away from it, and Jupiter would be about 10 inches away and would be the size of a mote of dust.) In our model the stars themselves—the grains of salt—would have to be separated by about 7.5 miles. (You can understand why stars rarely collide.) The floor I would need to spread them out on would be about one and a half times the distance between Earth and the Moon.

The message of this little experiment is that space is mainly empty space. And there are enormous numbers of stars out there—a lot of salt grains—and many opportunities for variety in the stars and the stuff that might be orbiting around them.

*We're looking for a mote of dust next to a grain of salt 7.5 miles away—at the closest.*

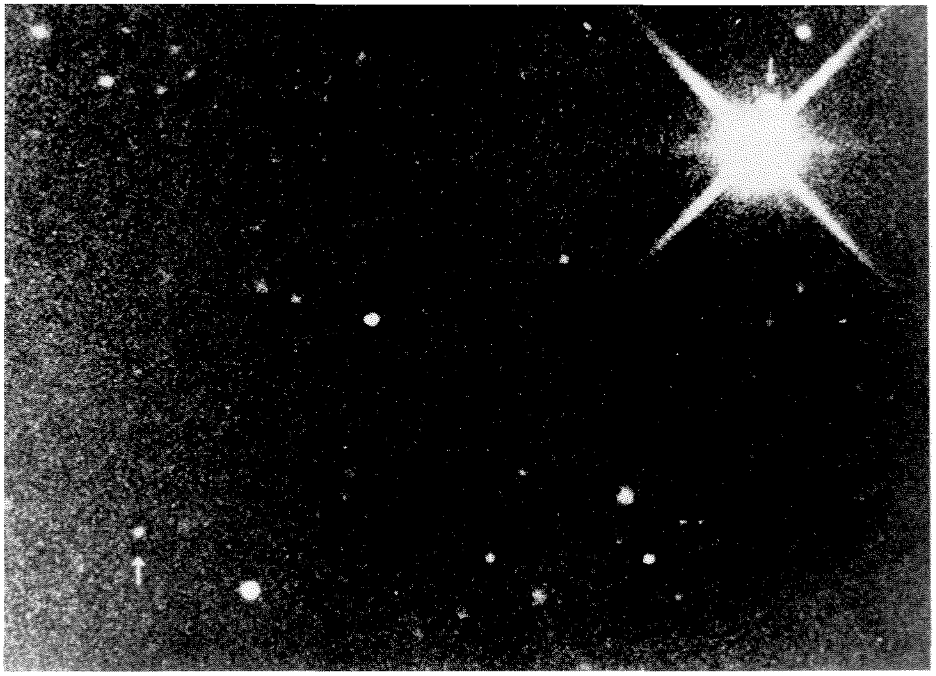
So, how are we going to find a planet orbiting around a star? We're looking for a mote of dust next to a grain of salt 7.5 miles away—at the closest. If we were to look at the Earth from far away, we could in fact determine that there was something very peculiar about this planet (even if we saw it 50 years ago before we were broadcasting TV). We would know from its spectrum that the Earth's atmosphere is composed in part of oxygen and methane, which normally should not coexist in equilibrium in the atmosphere. Something has to be continually supplying the methane and the oxygen, and the thing that's doing it is biology. If we were to measure a planet's spectrum and see oxygen and methane in its atmosphere, we would have to conclude that no known geological processes could maintain this kind of chemical configuration and that there must be something—perhaps biology—acting to do that.

Seeing the atmosphere of an Earth-like planet from such a distance, however, is going to require putting an immense construction such as the Arecibo Radio Telescope, which is 1,000 ft. in diameter, in Earth orbit or on the Moon and operating it at visible wavelengths. Since projects like this would cost multiple billions of dollars, it was important to look for something we could do in the meantime with current technologies and current budgets—something on the planetary mission scale in the $100-million range.

If we back off from looking for Earth-like atmospheres, what else can we do? We could look at nearby stars for a Jupiter-like planet, which is 10-11 times the size of the Earth. It's both farther away from the star and bigger. But still, Jupiter in visible light is about a billion times fainter than the center star, and looking for something very faint next to something bright isn't easy. We can't look for anything more than about 10 percent larger than Jupiter though, because that's the limit on planet size. For example, if you cram Jupiter and Saturn together to make a larger planet, you actually end up getting a smaller planet. Since the atoms in the center of Jupiter are already squashed together under pressure, the more mass you add, the more those atoms are crushed, and the planet begins to contract. The interior would get hotter and hotter until it ignites and becomes a star.

In looking for Jupiter-sized planets around nearby stars, we can derive some clues from what we already know about the way planets form. We know that in our solar system the planets lie in a flattened disk; they're all more or less in the same plane. When the cloud out of which the solar system formed collapsed, with the sun condensing in the center, it tended to flatten down at the poles with angular momentum holding the remaining debris—ice, rocks, and so on—in orbit around the center. As pieces of the debris collided with each other, coalescing into planets, they lost energy and wound up in circular orbits in the same plane. Almost all the angular momentum of the original disk resides in the planets; in fact, Jupiter contains more than 90 percent of the angular momentum of the solar system. This process of gravitational collapse also occurred in the individual planets, leaving debris in the form of satellites and rings.

Gravitational collapse isn't a very efficient mechanism; it's almost impossible to sweep up all the debris into the Sun, so, if other stars formed in the same way as the Sun—and it's likely they did—then it's a very reasonable assumption that they also left behind debris and planets. The formation of planets leaves characteristic signatures (areas swept clean of debris) in the disk, but because such disks are obscured by the bright light from the stars themselves, they have been impossible to see until recently. This began to change in 1983, when IRAS (the Infrared Astronomical Satellite) mapped out the entire galaxy in infrared wavelengths invisible to the human eye. The Milky Way lights up brilliantly in the infrared, even its center, which is normally obscured by dust at visible wavelengths. IRAS showed us some extraordinary things. Most exciting to me was the evidence that some nearby stars are surrounded by cold material—material in orbit around the stars.



**Triton (arrow), one of Neptune's satellites, is a factor of 230 less in brightness than the planet, and is nearly obliterated by the scattered and diffracted light from Neptune. A coronagraph solves this problem, allowing a better look at Triton. (A still better view will be taken by Voyager II when it encounters Neptune and Triton in August.) The arrow at lower left indicates Nereid, another satellite of Neptune.**

With these hints from IRAS about which stars would be interesting to look at, Brad Smith (professor of astronomy at the University of Arizona) and I set out to find a star with a disk around it, using the 100-inch telescope at the Las Campanas Observatory in Chile. On page 2 is a photograph of what we found—Beta Pictoris. It's 50 light-years away, one of the nearest thousand or so stars.

In a normal image of Beta Pictoris light from this star is so bright that it obscures any hint of a disk. Fortunately, we can now record these images, using special optics to mask out the light from the central star, and then further process the images in a computer. What we now see, sticking out from behind a blocking mask, is an edge-on disk extending far out beyond the star—about 20 times the radius of our own solar system. Although we're seeing the disk edge-on in this picture and can't see the center directly, our work has indicated that the center of the Beta Pictoris disk is, in fact, clear of material. We believe that this is because planets have already formed in the center of this disk, and, indeed, we may be looking at a very young solar system—perhaps only 1 to 2 percent of the age of our own, with much of the raw material that made the planets left over in an extended disk far larger than the extent of the planets. It took an extraordinary instrument and extraordinary observing conditions to make this photograph because the disk is about 100 million times fainter than the star. We have since seen it again and again with different telescopes, so we're sure that this isn't just an artifact.

Although IRAS has provided some clues about where to look for potential planetary systems, it hasn't enabled us to see a planet. There are some indirect techniques used to look for planetary systems. An orbiting planet will gravitationally disturb a star, causing it to wobble slightly, and a technique called astrometry can pick out a star's wobble against background stars. This same wobble will cause the star to accelerate toward and away from Earth, so it's also possible to see small Doppler shifts in the spectral lines of such a star. But these indirect methods require long observation times—from years to decades. We wanted a direct detection method—something we could see right away. Once you get a picture, once you've separated the light from the star, then you can make measurements on that light independent of the star and look for evidence of oceans, atmospheres, and so on.

To detect a planet directly we had to solve the problem of finding a very dim object next to a bright one. For example, in the picture of Neptune and its satellite Triton above, Triton (arrow), which is only a factor of 230 less in brightness, is nearly obliterated by the diffracted light and scattered light from Neptune. Diffraction comes from the telescope mirror's finite size, which causes light to spread out. Fortunately this problem was solved in the 1930s by French solar astronomer B. F. Lyot, who tired of traipsing off with all his gear to places like New Guinea to study the Sun in eclipse. A total solar eclipse, when the Moon covers the Sun, leaving only the the Sun's corona

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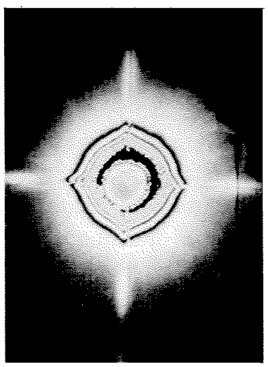
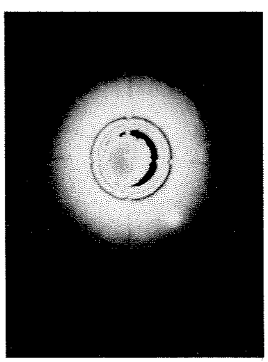




**Sirius, the brightest star in the night sky, is shown with the pupil mask (bottom) and without (top). The mask removes diffracted light, revealing a companion star, which is fainter than Sirius by a factor of 10,000.**

visible, has long provided a valuable opportunity to study our star. Lyot thought up the idea of simulating these conditions in the telescope with a coronagraph, an instrument that sticks a little mask in front of the Sun and essentially creates a miniature solar eclipse in the telescope. Today we use that same instrument on telescopes to create star eclipses. Lyot's coronagraph gets rid of 99 percent of diffracted light—a factor of 100.

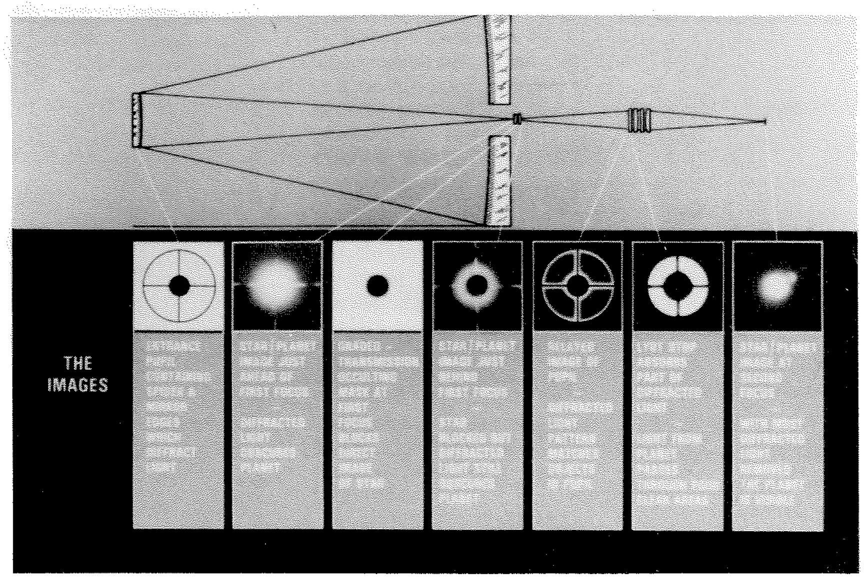
To photograph Beta Pictoris at the Las Campanas 100-inch telescope, we used a more sophisticated version of that original coronagraph affixed to the telescope base. It's a compact instrument, four feet long, complete with optics, including in the camera system a charge-coupled device (CCD), an extremely sensitive and efficient detector of photons. We then processed those images by computer to enable us to see these faint disks. Using the coronagraph, all the light that falls on the 100-inch mirror is focused on a dot about the size of a pinpoint. The tiny mask is suspended by silk monofilaments about 10 microns in diameter—about one-tenth of the diameter of a human hair. Masking off the light from the star has a peculiar consequence further down the telescope: Diffracted light from the telescope mirror is concentrated around the edges of the mirror. We place a second mask (called a pupil mask) in the coronagraph, which blocks off this concentrated diffracted light.

Sirius, the brightest star in the night sky, is shown at left with and without the pupil mask of the coronagraph. Without the mask, diffracted light comes out as bright streaks, which make it difficult to see Sirius's companion star. With a coronagraph (the lower illustration) all that streakiness has disappeared, and the companion star is easily visible.

Our calculations have shown that we need to be able to reduce diffracted light by a factor of 1,000—get rid of 99.9 percent of it. And we've come close to this by using transparent masks instead of solid blocking masks in the coronagraph. Our transparent masks, which are dense in the center and tail off at the edges—like a fuzzy, blurry spot—allow us to concentrate the light in the telescope more efficiently, so that we can then remove more of it. In laboratory experiments we're now only a factor of 2 (instead of 10) away from what we need, and we think our goal is within reach.

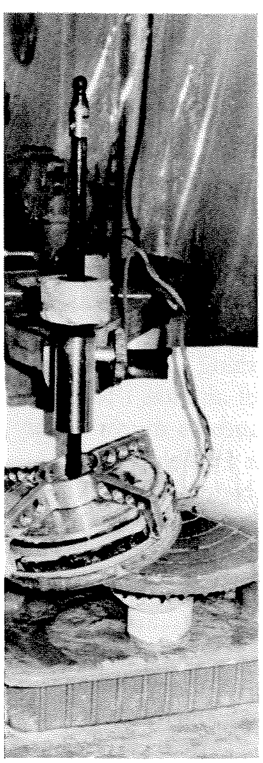
Once we could reduce diffracted light by a large factor with our high-efficiency coronagraph, we needed a mirror that could reduce scattered light by a comparable amount. Otherwise we wouldn't really be any further ahead. Scattered light is caused by imperfections in the telescope mirror itself. Up until now the 2.4-meter Hubble Space Telescope mirror was the smoothest astronomical mirror ever built. The instrument that polishes it is about a foot in diameter. It turns out that that kind of spatial scale on the mirror is a very important one; any kind of tool signatures, any kind of deviation in the shape of the mirror over an area the size of the palm of your hand, say, hurts you. It scatters light into the angles where you expect to see planets. So maintaining exceptionally smooth mirrors at these relatively large spatial scales is the only way to reduce scattered light. For example, if you imagine a mirror the size of the United States, it isn't the little things like mountains or valleys that bother us. What we worry about is the average height of the land over an area the size of, say, Arizona. We need to be able to control the average height of something the size of Arizona to within two-tenths of an inch. To do this, we calculated that we need a mirror about 15 times smoother than the Hubble Telescope—an intimidating realization because that telescope is the smoothest one ever built for astronomy.

But it turns out that astronomy has not been pushing smooth-mirror technology, because there was no need for it as long as the diffracted-light problem existed. But microlithography has. The people who wanted to create smaller and smaller microcircuits required smoother and smoother mirrors to image the masks that create the photoresist patterns. We discovered that for years the Perkin-Elmer Corporation has been building its Micralign mirrors five times




**The optical components of the Circumstellar Imaging Telescope are shown schematically at right. The figure also shows the distribution of diffracted light at various stages in the optical train in both pupil and focal planes. The coronagraph isolates and removes diffracted light from the focal plane, allowing a faint planet to be detected near a bright star.**

**Below: A supersmooth mirror developed for microlithography is polished further for a new career in astronomy.**



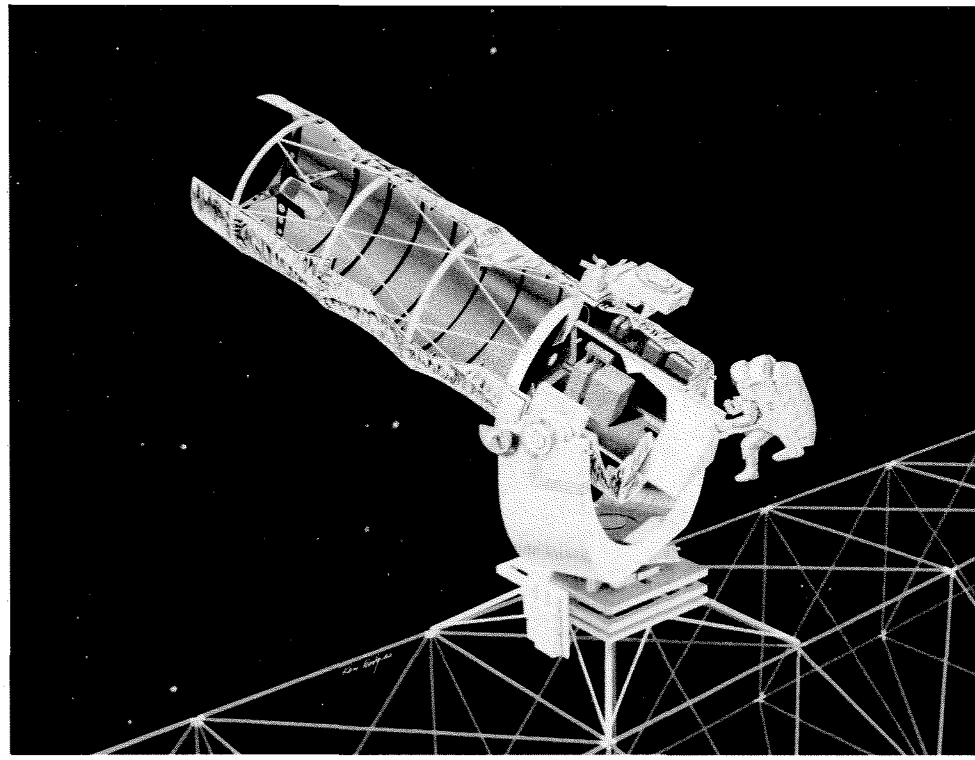
smoother than the Space Telescope mirror. They just crank them out on an assembly line. This was news to me. For years NASA committees have been telling us that building these direct-detection telescopes was impossible; that we shouldn't even think about it. So JPL and Perkin-Elmer started some joint experiments to see if we could continue the polishing process to make a mirror as smooth as we needed. (Just as astronomy was aided here by the gains made in microelectronics, our demands are now contributing something back to improve microelectronic technology.)

Besides being able to polish a mirror smoother than any that had ever been made, we needed to be able to measure it. It doesn't help you to polish a mirror if you can't tell whether it's really smooth or not. Luckily, again, technology had caught up with our desires, and measurement techniques are good enough to tell us what we need to know. A couple of months ago we finished polishing a supersmooth mirror that is nearly flight quality. It can reduce scattered light by a factor of 700-800 (we need 1,000). So we've gone from *wanting* a mirror 15 times better than the Space Telescope to actually physically *having* one that's about 12 times better.

This mirror is 30 cm in diameter; eventually we will need a 1.9 m mirror for our direct-detection mechanism—the Circumstellar Imaging Telescope (CIT)—which will have to be flown in orbit above the Earth's atmosphere. We would like this telescope to be a free flier—like the Hubble Space Telescope, which will be launched from the Space Shuttle next December. But to be realistic (politically and financially) we think we have a better chance of getting it on the Space Station as an attached payload. The Space Station is wobbly—astronauts are inside bouncing off walls and eating meals and flushing toilets and doing all sort of things that create a disturbance, but we think we can live with those disturbances.

The Circumstellar Imaging Telescope will be able to explore a portion of what astronomers call phase space that is unavailable to other types of telescopes. The 10-meter Keck Telescope, for example, being built on a Hawaiian mountaintop by Caltech and the University of California, will be able to gather enormous amounts of light to see things that are incredibly faint and far away. Orbiting above the Earth's atmosphere, the Hubble Space Telescope will explore a different realm of space—those objects that need high resolution, a greater degree of clarity. But neither of these can see what's happening near very bright objects. This is uncharted territory, interesting because the most exciting objects hide behind the brightness.

We think we will be able to detect and photograph planets around nearby stars with this instrument—in hours or tens of hours instead of years or decades. But that's only the hardest thing it has to do; it's admirably suited to other tasks as well. For example, if we had a coronagraph in orbit now, we would be able to see, despite their brightness, the shells of expanding gas around the nearby supernova that exploded in the Large Magellanic Cloud last year. But since we don't have a coronagraph up there now,



**By the mid-1990s the Circumstellar Imaging Telescope, with its 1.9-meter super-smooth mirror, could orbit the Earth as an attached payload on the Space Station.**

*And then the king of Spain came to mind. I mean, the guy's got a track record, right?*

we'll just have to wait for the next nearby supernova; it's only been 500 years since the last one. We also want to study quasars, the most remote objects in the universe. The closest one is about 800 million light-years away. We'd like to explore the fuzzy regions near the quasars, to understand how the quasars form jets and what the material around them is. The active nuclei of galaxies might be another target.

So far our project has been funded by discretionary funds from Lew Allen, director of JPL. He took a gamble on this wacky idea of ours, and I'm pleased that we've been able to deliver something ahead of schedule, at a lower cost and better than we expected. Now we feel more confident than we felt a year ago that there are much fewer risks associated with building one of these large mirrors. But before we try to put an expensive, heavy 1.9-meter mirror in Earth orbit—the $100 million project—we want to take the intermediate step of building a 1-meter mirror to operate at 1 g (an orbiting mirror would have to be built for 0 g and so couldn't really be tested on the ground) and test it in a laboratory to understand how it works and learn to operate it more efficiently. Then we could send it up to 100,000 ft. or so in a balloon. On the ground, the atmosphere tends to break an image up into several pieces, which blurs it; at 100,000 ft. it breaks up into only one piece, and you get a sharply focused, but wobbling, point source instead of a big blob of an image. The light blocked by the occulting mask of the coronagraph could be reflected into another instrument and used to point the telescope to track the wobbling image. We'd have the potential to detect planetary systems around the nearest half dozen or so stars in one night, and could even send the instrument back up a few months later to confirm any results. If we look at half a dozen stars and *don't* find anything, it wouldn't really mean very much statistically; we wouldn't be discouraged. But if we *do* find something, it would mean a hell of a lot.

We could look for new worlds for a mere $5-10 million and do it by the early 1990s. I have in mind October 1992, the 500th anniversary of Columbus's discovery of the new world. I couldn't sleep at night thinking about this. There must be someone I could ask for $10 million. I thought long and hard—and then the king of Spain came to mind. I mean, the guy's got a track record, right? Five hundred years ago he did it. And if he's not interested, maybe I could try Portugal. They missed out 500 years ago, and maybe they'd like another chance. □

*In addition to the first pictures of another solar system, Rich Terrile has discovered Saturn's innermost moon and two moons of Uranus. As a member of the technical staff at JPL and group leader for planetary astronomy, he's part of the Voyager imaging team and, in more down-to-Earth projects, has spent 15 years observing at both visible and infrared wavelengths at Palomar Mountain, Mauna Kea, and Las Campanas. Terrile graduated from the State University of New York at Stony Brook in 1972 and earned his MS (1973) and PhD (1978) at Caltech.*