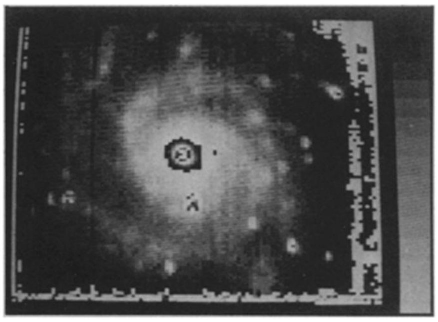
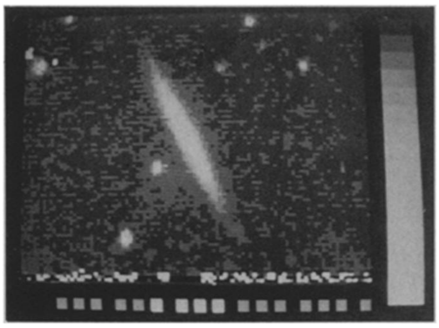
CCDs Astronomy's Superchips

A developing semiconductor technology has entered the realm of observational astronomy and almost overnight expanded the depth of our visible universe

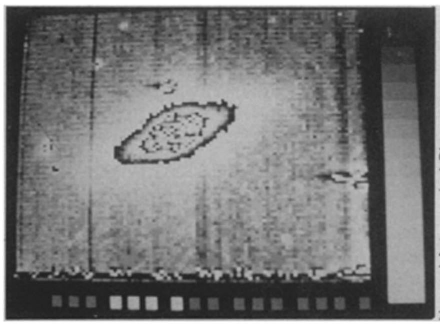
BY JANET RALOFF



M101



NGC 5023



NGC 4526

Harvard Astronomical Observatory

It's only a small wafer — one square centimeter of silicon impregnated with electrodes — but already it's advanced to the front lines of observational cosmology. These charge-coupled devices — better known as CCD's — have already detected the rings of Uranus and will soon be seeking primordial galaxies on the farthermost edges of our visible universe.

In the few years since they entered the astronomical arena, CCD's have created a minor sensation. And most of the still small number of users predict they will be the detector "of choice" for the entire observational community within a few more years.

In simple terms, CCD chips are little more than a layer of metallic electrodes and a layer of silicon crystal sandwiching an insulating layer of silicon dioxide. Like the retina of an eye, a CCD registers information about the precise intensity and dimensions of a light source, then shuttles the information to a brain for processing. In this case the brain is a computer and the retina an array of "potential wells" that collect light photons like little buckets. CCD's register light as the presence of electron-hole pairs in the potential wells. The increment of electric charge in each well is proportional to the intensity of light. The array of coupled buckets transfers its charge-information directly and sequentially, in digital form, to a computer which then reconstructs a precise image of the objects viewed.

The device gets its name from the fact that each well is coupled to the next and transfers its information, "bucket brigade" fashion, to the adjacent well and on out to the computer. Currently used CCD's come as arrays of wells, of "pixels," in sizes from 100 by 100 to 400 by 400. "But there will be [arrays of] 800 by 800 on a telescope within a year, I am sure," says James Westphal of the California Institute of Technology. As principal investigator in the NASA program to design a complicated camera scheduled to fly aboard the Space Telescope in 1983 or 1984, he has privileged access to the biggest and best chips as soon as they emerge from Texas Instruments' production laboratory. At present, Texas Instruments is the major producer of CCD's.

Experiments using CCD cameras made from these chips have already detected the faint rings of Uranus and 24th magnitude stars. But those chips are only pale experimental prototypes compared with the 800-by-800 pixel chips that will fly on the Space Telescope and on Galileo (formerly the Jupiter Orbiter and Probe mission).

"I was the first one to use the CCD for astronomical observing," says Bradford Smith of the University of Arizona. "I got the first one... because really nobody else was interested. The Jet Propulsion Laboratory had this device and was looking around for somebody to try it out on a telescope .... We set it up and in just an engineering run we discovered clouds in the atmosphere of Uranus." The unexpected find justified his belief in what he now calls a "remarkable" device.

Groups at Harvard University and Princeton University are also designing CCD cameras. But they lament the fact that they must settle for small, physically inferior 100-by-100 chips created for the commercial-television-camera market while, according to Princeton's David T. Wilkinson, "the CCD's that Texas Instruments are developing for JPL are very close to what I would consider, at this point, the ultimate detector for astronomy."

Limited access to the superior chips is the principal disadvantage of CCD's today, and "a serious one," Wilkinson says. But it also is one that could be solved within the next six months to two years, Westphal told SCIENCE NEWS. Texas Instruments is under NASA contract to make nine chips, eight for the Space Telescope, one for Galileo. They may try making a hundred or more chips to get the nine best for NASA. "Once those nine sensors have been selected," Westphal explained, "the rest... will rattle down into the ground-based astronomy community by some mechanism that has not been defined" yet by NASA.

And the community waits eagerly, for CCD's promise a wealth of advantages over the imaging devices it now uses. One of the most important advantages is in quantum efficiency, particularly in the red spectral regions. Quantum efficiency is the percentage of incident photons that are converted to photoelectrons or, in the case of film, the percentage that act on sensitized grains in its emulsion. High quantum efficiency reduces the time needed to make exposures. The quantum efficiency of film is less than one percent, says Herbert Gursky, associate director of optical and infrared astronomy at the Harvard-Smithsonian Center for Astrophysics. "The best we can do with electrical devices — photomultipliers, image tubes, television-type cameras — is between 10 and 20 percent ... but with CCD's, in principle, the quantum efficiency can be 100 percent."

Perhaps more important, "the CCD is the first detector that offers imaging capability—so that you can actually take pictures —in the deep red [spectral range] and still get good quantum efficiency," says Wilkinson.

In fact, Wilkinson's group at Princeton was motivated to build a CCD camera by their interest in primordial galaxies. "These are the galaxies that are just forming; the stars have just started to precipitate out of the primordial gas and condense into galaxies," he explains. "This happens at a very high redshift," where their spectral energies are all pushed toward the red end of the spectrum. "We're not sure exactly where, but it's probably somewhere at a redshift factor of between five and 30."

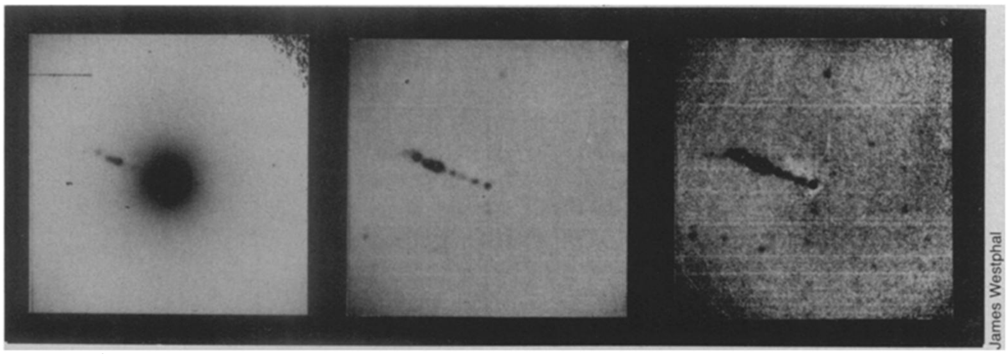
"It's a risky, speculative program," he goes on, "because we're looking at objects that haven't been seen before and are trying to guess what their properties might be

.... Certainly primeval galaxies are out there; its just a matter of guessing what they look like, getting high sensitivity in the red, and deep pictures of the sky."

Wilkinson says that although observations with their CCD camera have yet to turn up any promising candidates, their best opportunity will occur in September, when their camera will go on the four-meter telescope at Kitt Peak.

If one doesn't find primeval galaxies there, he says, "then you have to back up and work your way out. The best way to do that seems to be to find and measure properties of high-redshift galaxies in very-high-redshift clusters." Two graduate students in his physics group are looking at the spectra of such objects with their CCD camera.

On a more conventional tack, some members of the group will undertake a search for halos about galaxies to find the missing mass of the universe. "There's some indication that what we're seeing in nice, pretty spiral galaxies is not by any means all there is," Wilkinson says. "There is a lot of dark matter in the form of little red stars or something. The CCD is an excellent detector to look for such faint red halos." Princeton's Ed Loh has already detected one very red halo about NGC 3877 that looks promising, according to Wilkinson. But "one certainly won't believe this is a general property of galaxies unless one sees this in several. One has to go much fainter than can be done in photographic emulsions to do this."


James Westphal

Photos of M87 taken with CCD's by James Westphal's group at Cal Tech. From left to righ., jet and galaxy, galaxy removed 4X stretch, 16X stretch.

Harvard's Robert Leach says "there definitely appears to be a halo" around NGC 4565, based on preliminary analysis of observations made by a Harvard colleague with their CCD camera. But Leach says his own work on the photometry (measured intensity of the light output) of distant, faint galaxies tends to exploit the properties of CCD's better.

In the past, galactic photometry was done primarily with single-aperture photomultipliers. But when one examines extended objects, such as galaxies, through a circular pin-hole aperture, part of the image is always cut off, Leach says. To compensate, a correction factor is added. With CCD's, one can measure directly and accurately the entire object or many objects simultaneously.

Planetary observations also benefit from the CCDs' red sensitivity. Brad Smith's studies of Uranus (SN: 3/12/77, p. 169) and Jupiter involve using a methane-absorption band in the planet's atmosphere at about 8,900 Å. The methane absorbs all the light in the band, he says. When looking for faint rings or satellites, one simply diminishes the light from the planet body by imaging in the band. "In the case of Uranus, for example," he said, such imaging "changes the reflectivity close to Uranus, from about 60 percent as we see it in visible light, to about one percent; there's so much methane in the atmosphere of Uranus that the planet appears very, very dark." He says his CCD observations turned up images of its newly discovered and very faint rings.

A problem when using any detector is how often recalibration is necessary as the detector's properties drift and change. The more often you calibrate, the more difficult observing becomes. If you do calibrate often, says Smith, "then you worry about whether it's changing and how much between calibrations." But not with CCD's, he says. "They are *extremely* stable, both photometrically and geometrically." This becomes especially important for components chosen for use aboard spacecraft where recalibration is difficult or impossible, Westphal adds.

Another important advantage of CCD's is their lack of noise — sporadic, equipment-generated fluctuations in the accuracy of the data signal that can obscure significant real fluctuations in the data. When cooled to temperatures around −100°C they are very quiet. They are also very linear in their light response, which means that a doubling in the amount of incident light will bring a doubling in the electric-charge registered by the potential wells. In contrast, photographic film is very nonlinear. What's more, the linearity of film will vary with the intensity of light, Smith says.

A detector's dynamic range — its ability to measure the light intensity of both very faint and very bright sources at the same time — is very important; it affects the number of exposures an astronomer must make to get accurate readings of all objects in the visual field. According to Westphal, CCD's "have a dynamic range that's a factor of 10 — or close to 100 maybe — bigger than any other type of detector that you can use to make a picture."

A related feature, especially important now that availability of good chips is such a problem, is that you can't burn out a CCD chip from overexposure. "If you send too bright a star into an image intensifier or photoelectric photometer, you can ruin it," Smith cautions. "Not true with CCD's. You can let the sun shine on them and all they'll do is saturate. There's no damage."

For all their virtues, CCD's do have limitations, size being the predominant one. "For example," Westphal explains, "if you want to take a picture of a very large amount of sky at one time, you do it with a 14-inch-by-14-inch photographic plate in a Schmidt camera. That's not going to be replaced by CCD's in any time that I can dream of." The reason is that data-processing equipment would overload with the high-resolution detail generated by even one small 1,200-by-1,200 chip, the astronomers believe. So photographic cameras will remain the detector of choice for wide-field imaging, leaving CCD's to zero in on points of interest.

Westphal says that wiring a modular array of CCD chips together into a mosaic might be one technique to increase the resolution or coverage of a CCD camera. Two such four-chip mosaics will be used in the "wide-field planetary camera" on the Space Telescope. In the camera's wide-field mode, Westphal says, the mosaic will view a region 160 seconds of arc on a side. A second, fitted with magnifying lenses, will focus on a patch only 60 seconds of arc on a side to peer deeper into space in search of faint objects.

These CCD chips will also bear a special optical coating — an organic phosphor — that converts ultra-violet to the visible range. The result is a chip whose sensitivity extends from the "extreme ultra-violet, I guess, down at 500 Å," to about 11,000 Å without hampering the quantum efficiency in its visible and infrared range. It will match the quantum efficiencies of its best competitors in the blues, Westphal says, and greatly surpass any detector in the visible and red regions.

Since its invention in 1969 by Bell Laboratories scientists George Smith and Willard Boyle, the versatile CCD chip has evolved quickly. But its evolution is far from over. Astronomers expect to see 1,000-by-1,000 array chips within only a few years. They'll help remap the skies and extend its boundaries. They may even give small, university telescopes a new lease on life by extending their resolution and ability to do competitive research.

Westphal speculates that "in the next three or four years, or some time scale like that, every observatory will have [a CCD camera-detector] and be using it. They're wondrous things, but they're going to be much more wonderful." ☐