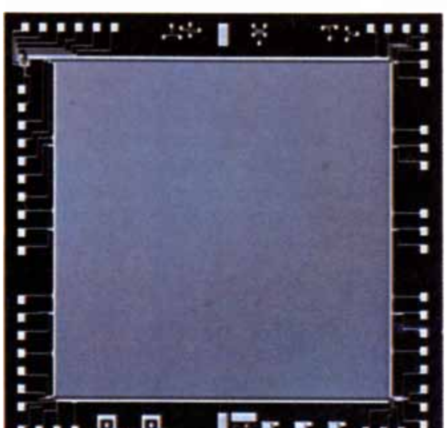


NEW VIEW OF A SPIRAL GALAXY was obtained by means of the microelectronic light detector known as a charge-coupled device (CCD). A CCD sensor similar to the one used to record the image of the galaxy is shown enlarged about six diameters in the photograph at the left; the microcircuit, which is constructed on a square chip of semiconducting silicon 10 millimeters on a side, has 250,000 pixels, or individual picture elements, in its imaging section (*central square area*). The picture of the galaxy was made by first exposing three separate CCD frames at the telescope through blue, green and red filters and then reading them out through a set of identical filters onto color photographic film. A similar procedure can be followed with a color-television monitor by having the data from the three CCD frames drive the set's three electron guns. Color composites of this type are particularly helpful for identifying astronomical objects or regions that differ in their temperature and hence in the wavelength of the light they emit. Here, for example, the galaxy's spiral arms, which include many hot young stars, are bluer than the cooler dusty regions between the arms. One can also pick out a number of foreground stars of various colors and at least one faint background galaxy (*bluish oval at top center*). The CCD images were obtained with the aid of the 100-inch du Pont telescope at the Carnegie Institution of Washington's Las Campanas Observatory in Chile. This galaxy, designated NGC 1232, is in the constellation Eridanus at a distance of about 100 million light-years.

Charge-coupled Devices in Astronomy

Microelectronic technology has presented astronomers with a sensitive new radiation detector that is expected to improve the accuracy of many crucial observations

by Jerome Kristian and Morley Blouke

Astronomy, the oldest of sciences, concerned with nature on the largest scale, is being aided by the newest developments in microelectronics, the most advanced technology of the very small. The tiny new television sensors called charge-coupled devices (CCD's) are providing a new view of the heavens, and with unprecedented sensitivity. The history of astronomy is in large part the story of a continual search for more efficient and more accurate ways of measuring the meager light from stars. The kinds of detectors available to astronomers have always limited the data that can be gathered and the problems that can be attacked, and they have constrained, if not dictated, the direction of the advance of knowledge. Over the past few years the search for more light has combined with explosively fast developments in electronics, solid-state technology and computers to provide astronomy with the means to make measurements that were undreamed of 50 years ago and were only a vague hope just five or 10 years ago. These measurements promise dramatic new insights into the dynamic processes of the growth and decay of stars, galaxies and the universe.

Before we describe the new detectors let us briefly survey the history of astronomical light detection. Until the 17th century astronomy was done exclusively with the unaided eye. The eye is a very good light detector, perfectly tailored to its everyday uses, but it has its limitations for astronomy. Its efficiency can be as high as a few percent, which is respectable even compared with some modern light-detecting devices. The eye, however, responds only to a limited range of colors, from blue through red. Radiation in the neighboring ultraviolet and infrared regions of the spectrum is invisible. The eye can also discern subtle differences in light intensity but is a poor judge of absolute brightness. Although the eye works well over a remarkably wide range of brightnesses, it cannot store light for more than a few tenths of a second. No matter how long you look at the night sky you will not see stars fainter than some limiting magnitude.

The invention of the telescope in the early 1600's opened a new world. By collecting and concentrating the light from a larger area the telescope in effect increases the eye's sensitivity. As a result fainter objects can be seen, an improvement that was immediately evident to Galileo, who remarked that with his rudimentary instrument he could see "stars, which escape the unaided sight, so numerous as to be beyond belief." In order to observe fainter and still fainter objects astronomers have continued to build larger and more ingeniously designed telescopes.

Until late in the 19th century, however, the detector at the focus of the telescope was still the eye. Then came the new art of photography, which offered such marked advantages that it quickly became the chief detection method for astronomy. A photographic emulsion is not much more sensitive than the eye, but it has the great advantage that it can build up a picture of a faint object by accumulating light for a long time. A photograph is also a permanent record that can be taken to the laboratory, studied and kept for later reference. Modern photographic emulsions are sensitive to a wider range of wavelengths than the eye is: from the ultraviolet region to the near-infrared. Brightness can be measured photographically to an accuracy of better than 10 percent. There is still a limiting faintness, however, beyond which an object cannot be detected on a photograph; for long exposures the ever present background light from the night sky eventually saturates the entire emulsion.

After World War II photomultiplier tubes became widely available for accurate measurements of the brightness of astronomical objects. In a device of this type a photon, or quantum of radiation, strikes the surface of a photoelectric material, which responds by emitting an electron. The electron is accelerated by an electric field to a high energy, thereby constituting a small current, which is amplified within the tube to generate a measurable pulse of electricity. Photoelectric surfaces have efficiencies as high as 20 percent, and they can be made sensitive to a wide range of wavelengths: from the far-ultraviolet to the infrared.

The response of a photomultiplier is linear, that is, the output in units of electric current is directly proportional to the input in units of light intensity. Accordingly it is a straightforward matter to measure the intensity of the detected light with great accuracy. Individual photoelectrons can be distinguished, and indefinitely long exposures can be made for extremely faint objects. A major disadvantage of the photomultiplier is that it can observe only a small part of the sky; as a result stars must be measured one at a time, and extended objects such as galaxies must be sampled point by point, a task that is very costly in terms of telescope time.

More recently the technology of television and electronic image amplification has been adapted to astronomy, with the aim of combining the accuracy and unlimited exposure time of the photomultiplier with the extended field of view of the photographic plate. Such an approach should make it possible to accurately measure many stars or an entire galaxy with a single exposure. Various devices of this type have been proposed and tested for astronomy, and the range of possible schemes is still expanding. Most of the devices tried so far start with the light striking a photoelectric surface; a variety of methods are then employed for amplifying and measuring the resulting flow of electrons. Charge-coupled devices operate in a somewhat different way, which we shall now describe.

Recording a pattern of light with a CCD is rather like measuring the distribution of rainfall over a field by setting out an array of buckets before the rain and afterward moving the buckets on conveyor belts to a metering station where the amount of water in each bucket is recorded. In a CCD the "buckets" are electron-collecting zones of low electric potential created below an array of electrodes formed on the surface of a thin wafer of semiconducting silicon. The zones, called potential wells, are moved about within the device to an output amplifier by changing the voltage on the electrodes in a systematic manner.

When a photon strikes the silicon, it is very likely to give rise to a paired entity consisting of a displaced electron and the "hole" created by the temporary absence of the electron from the regular crystalline structure of the silicon. Hence a CCD resembles a photomultiplier tube in the sense that both devices convert light into electric charge. The method of capturing and measuring the charge, however, distinguishes the operation of a CCD from that of other light detectors. In the case of the CCD, when a photon creates an electron-hole pair,

OPERATING PRINCIPLE of the CCD imager is depicted in this sequence of schematic diagrams, each of which corresponds to a small segment near the top edge of the device. The strips of gray and white bars function as a system of electronic conveyor belts. The white bars represent zones of low electric potential, called potential wells, in which the photoelectrons (*colored dots*) are collected; the gray bars are zones of higher electric potential that act as barriers to keep the electrons in the potential wells. The three vertical strips in each diagram are electron-conducting channels "buried" in the body of the device's imaging section; the horizontal strip across the top is the serial output register. Three pixels are shown in each channel. Each pixel is in turn subdivided into three parts: one part low (the potential well) and two parts high (the potential barriers). The heights of the three parts can be changed by means of three sets of electrodes called gates (not shown here), which run across the surface of the chip at right angles to the channels and work in concert to move the electrons along the channels. The electrons are kept from moving sideways out of the channels by permanent barriers called channel stops (*thick black lines*). In *a* the CCD is being exposed. Photons, or light quanta, enter the chip from the rear. Each photon can liberate one electron from the regular crystalline structure of the silicon. The electrons are promptly stored in the nearest potential well. After the exposure is finished the image is read out by moving the potential wells with their trapped charge packets in a systematic fashion. First the level of the next barrier toward the output register is lowered to the same level as the well. The electrons then divide between the two wells. Finally, the level of the original well is raised so that it becomes a barrier (*b*). The effect of this operation is to move the electrons one-third of a pixel upward. After two more shifts (*c, d*) the entire pattern of charge has been moved one full pixel upward and the electrons that were in the top row of pixels have been deposited in the output register. The same technique is now applied to move this row of pixels along the output register toward the left (*e, f*). An amplifier at the end of the output register measures each charge packet in turn, thereby reading out an entire row. The process is then repeated, with each row read out until the entire chip has been emptied of information.

the electron is immediately collected in the nearest potential well, whereas the hole is forced away from the well and eventually escapes into the substrate.

A CCD imager can be thought of as an array of serial shift registers. The image-forming section is covered with closely spaced columns, called channels. The channels are separated from one another by narrow barriers called channel stops, which prevent the charge from moving sideways. Each channel is in turn subdivided along its length into pixels, or individual picture elements, by a series of parallel electrodes (also known as gates), which run across the device at right angles to the channels. Each row of pixels (that is, one pixel per column) is controlled by one set of gates. A picture is read out of the device by a succession of shifts through the imaging section, with all the rows simultaneously moving one space at a time through the body of the device [*see illustration on opposite page*].

At each shift the last row of pixels passes out of the imaging section through an isolating region called a transfer gate into an output shift register. Then, before the next row is transferred, the information is moved along the output shift register, again one pixel at a time, to an amplifier at the end, where the charge in each pixel is measured. This final step constitutes a measurement of the original light intensity registered in each pixel. The technique for moving the electric charge about in this way is called charge coupling, and that is how devices operating on this principle got their name [see "Charge-coupled Devices," by Gilbert F. Amelio; SCIENTIFIC AMERICAN, February, 1974].

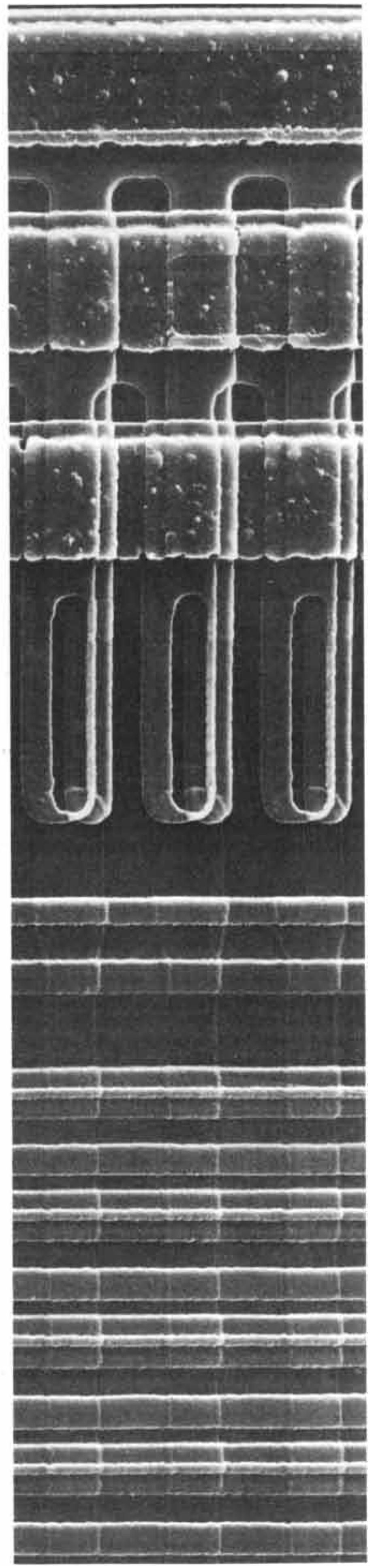
In effect the pattern of light falling on a CCD imager builds up an electron replica of itself, with more electrons created and collected where the light is brighter. The basic physics of the process is quite linear: doubling the number of photons at any pixel will double the number of electrons, until the potential well corresponding to that pixel is finally filled with electrons.

The first devices based on the charge-coupling principle were invented in 1970 by Willard S. Boyle and George E. Smith of Bell Laboratories. The first large image-forming CCD's, with more than 10,000 pixels each, were introduced in 1973. The advantages of such devices for astronomy were soon recognized by Gerald M. Smith, Frederick P. Landauer and James R. Janesick at the Jet Propulsion Laboratory of the California Institute of Technology.

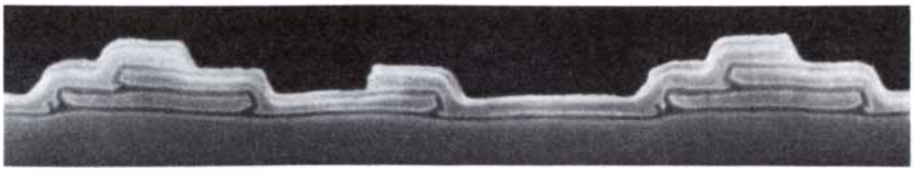
Later that year the Jet Propulsion Laboratory joined with the National Aeronautics and Space Administration and Texas Instruments to initiate a program for the development of large-area CCD imagers for space astronomy, in particular for the Galileo mission to Jupiter. The devices made by Texas Instruments for this program evolved from a thorough study of several approaches to the problem of designing and fabricating such microcircuits. CCD imagers have also been made by Fairchild Semiconductor, the RCA Corporation and the General Electric Company (GEC) of Britain, but here we shall discuss only the Texas Instruments detector.

In the Texas Instruments CCD all the circuitry for collecting, moving and counting the electrons is constructed on a single chip of silicon. The CCD is fabricated on a substrate of moderately high-resistivity *p*-type silicon: material in which the main charge carriers are positively charged electron holes. The overall fabrication process is similar to one originally developed by workers at Bell Laboratories. The first step is the creation of the five-micrometer-wide channel stops by diffusing boron ions through a mask into the exposed parts of the silicon substrate and then growing a thick (about 10,000 angstrom units) layer of silicon dioxide in those areas. Next the "buried" channels are created by implanting phosphorus ions in the areas not covered by the thick oxide. The phosphorus ions extend some 2,000 or 3,000 angstroms into the silicon. The dose of phosphorus converts the area below the surface into an *n*-type semiconductor: one in which the main charge carriers are negatively charged electrons. The *pn*-diode structure so formed localizes the potential wells at a position far from the interface between the silicon substrate and the superposed layer of insulating silicon dioxide.

The purpose of the buried channels is to enable the device to transfer charge



MICROCIRCUITRY ON SURFACE of a CCD imager made by Texas Instruments is enlarged some 1,500 diameters in this scanning electron micrograph made by John H. Tregilgas and one of the authors (Blouke). The area seen in the micrograph corresponds roughly to the one shown in the diagrams on the opposite page. A segment of the imaging section of the device occupies the bottom third of the micrograph. The raised horizontal bands are the electrodes for controlling the movement of the rows of charge packets upward through the channels. Each pixel is covered by three of these bands, which overlap to form a steplike structure. The less prominent vertical bands are the channel stops. The two raised horizontal bands just above the imaging section define the transfer gate through which the top row of pixels is transferred into the horizontal output register. The transfer gate isolates the imaging section of the chip from the output register. The output register is overlain by vertical structures that control the movement of the charge packets toward the amplifier (out of view to the left). The three broad horizontal bands near the top are aluminum contact strips that supply the voltage to the electrodes over the output register.



CROSS SECTION OF A PIXEL in the imaging section of the Texas Instruments CCD is enlarged about 7,500 diameters in this scanning electron micrograph. The cross section is along a vertical cut in the chip whose surface appears in the illustration on the preceding page, and it shows 1⅓ pixels. The characteristic steplike structure is formed by the three overlapping layers of polysilicon (polycrystalline silicon) that serve as the electrodes in this section of the device. Each first-level electrode is a polysilicon ribbon five microns wide (about a twenty-fifth of the diameter of a human hair) and 7.6 millimeters long, running in and out of the plane of the page. On a single chip there are altogether about 40 feet of such ribbon in the three sets of electrodes; the total volume of the polysilicon would fit into a cube half a millimeter on a side.

more efficiently by keeping the signal electrons away from the interface between the silicon and the silicon dioxide, where they can become trapped during the charge transfer. In general whenever a transfer is made from one well to the next, a small amount of charge is left behind. One effect of this residue is a blurring of the image; electrons that were generated at neighboring pixels are mixed together. In a square array 800 pixels on a side the charge packet farthest from the amplifier is transferred 4,800 times (2,400 times in each direction); in order to lose no more than 10 percent of the charge the loss at each transfer must be held to less than two electrons per 100,000. It is a measure of the power of the present technology that such a stringent standard is now routinely met.

The next step in making a CCD imager is to build the electrodes for collecting and moving the charge. After the formation of the buried channels a layer of silicon dioxide 1,200 angstroms thick is thermally grown on the surface to provide an insulating base for the electrodes. A layer of polysilicon (polycrystalline silicon) 5,000 angstroms thick is then grown on top of the oxide layer and is heavily "doped" with phosphorus to increase its conductivity. The first set of electrodes is made from the polysilicon layer by removing unwanted material by means of a standard photolithographic technique. The unprotected gate oxide between the electrodes is etched off and a new gate oxide of the same thickness as the original one is grown over the exposed channel. Simultaneously a somewhat thicker oxide layer is grown over the polysilicon to electrically isolate this first set of electrodes from the electrodes that are later formed over them.

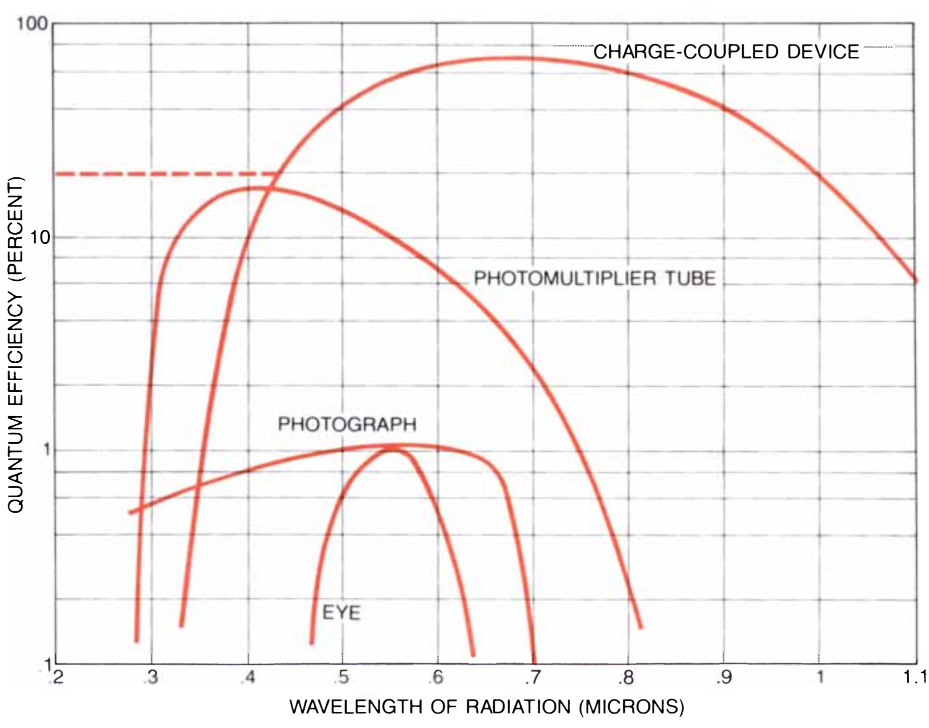
A second layer of polysilicon is then grown, doped and patterned to form the second set of electrodes. This step is followed by another etch-and-regrow cycle and by the deposition and doping of a third level of polysilicon, from which the third and final set of electrodes is made. The chip is finished by selectively etching holes in the oxide layer over the diodes and over specific contact points in the three polysilicon layers. Finally, a pattern of aluminum strips is formed by vapor-depositing aluminum over the entire surface and then defining the leads photolithographically. The aluminum makes electrical contact with the diodes and the polysilicon gates, and it leads to peripheral bonding pads where the chip can be connected with its external control circuitry.

Both silicon and polysilicon strongly absorb short-wavelength radiation, that is, radiation at the blue end of the visible spectrum. In order to improve the sensitivity of the CCD to blue light for astronomical observations, the imager is operated with the light striking the device from the rear; for this reason the imaging area is thinned to a thickness of about eight micrometers. A rim of unthinned silicon some 650 micrometers wide and 200 micrometers thick is left for support during mounting and for bonding the chip to the external leads.

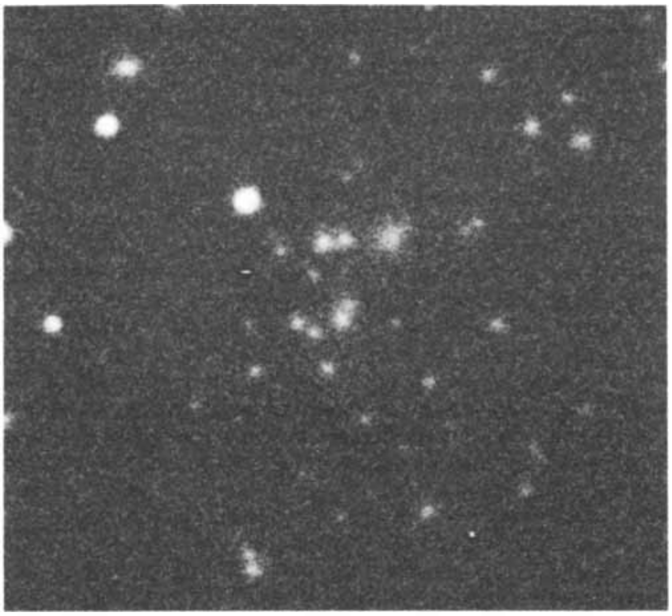
Two serial output registers are provided, one at the top of the array and another at the bottom, so that the image can be read out in either direction. Each register feeds into a simple two-transistor amplifier. One version of the Texas Instruments CCD has a square array of pixels with 800 pixels on a side, for a total of 640,000; each pixel is itself a square measuring 15 micrometers on a side. The total imaging section occupies a square area 12.2 millimeters on a side in the center of the chip, which has a total area of three square centimeters (17.8 by 17.8 millimeters).

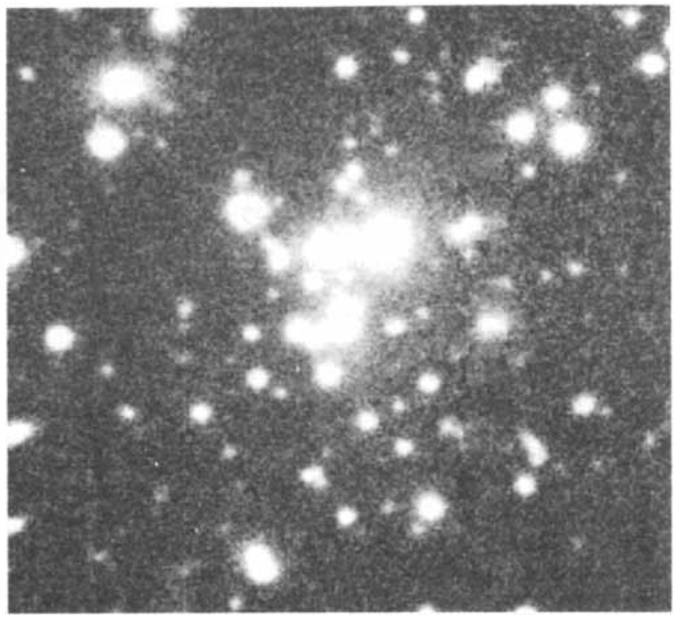
How does the new CCD imager compare with other light detectors available for astronomy? There are six major criteria for making such a comparison: quantum efficiency, noise level, dynamic range, color response, photometric accuracy and geometric stability. We shall briefly discuss each of these characteristics in turn.

An ideal detector would have a quantum efficiency of 100 percent, that is, it would generate a measurable response for every photon that struck it, without introducing noise, or spurious signals. In addition it would be sensitive to light of all colors, and it would give an accurate value for the brightness of the light at every point in a scene. It could be used



LIGHT DETECTORS available for astronomy today are compared in this graph in terms of their quantum efficiency (a measure of sensitivity) and their spectral range. The CCD imager is superior at all wavelengths except those in the ultraviolet region of the electromagnetic spectrum. The broken line represents the effect of a technique devised by James A. Westphal of the California Institute of Technology to overcome this deficiency by coating the CCD with coronene, an organic phosphor that converts photons of ultraviolet radiation into photons of light.





PHOTOGRAPH AND CCD IMAGE of an extraordinarily rich cluster of galaxies are compared. The cluster, Abell 1689, is in the constellation Virgo at a distance of about a billion light-years from our galaxy; its velocity of recession is a sixth the speed of light. Almost every object in both of the pictures is a galaxy. The photograph (*left*) was made with the 100-inch telescope on Mount Wilson by William C. Miller; the exposure time was 90 minutes. The CCD image (*right*) was made with the 60-inch telescope on Palomar Mountain by Donald P. Schneider, John G. Hoessel and James E. Gunn; the exposure was 25 minutes. Even though the photograph was made with almost three times the light-collecting area and more than three times the exposure, the CCD image reveals objects that are much fainter.

for indefinitely long exposures, in order to allow very faint objects to be detected, and it would be able to measure accurately both faint and bright objects in the same picture. Finally, it would be able to record the positions of the incoming photons accurately, so that the exact position of a star or of the spectral lines from a star could be determined.

Quantum efficiency is a measure of the sensitivity of a detector. Photoelectric materials now in service typically emit an electron for every five to 10 incident photons; therefore they have a quantum efficiency of between 10 and 20 percent. The quantum efficiency of the eye or a photographic plate is not as easy to define, but the concept is still useful for rough comparisons. The superiority of the CCD in this respect is evident from a plot of the quantum efficiency and the color range of several detectors [*see bottom illustration on opposite page*]. In contrast to the eye and the kinds of photographic emulsions commonly used in astronomy, which have a maximum quantum efficiency of a few percent, the new CCD detectors have a quantum efficiency that goes as high as 70 percent.

Since a more efficient detector yields more data, an observation made with such a detector can be done in less time or with a smaller telescope. For many problems in astronomy the largest telescopes available are now being used to their limit; improving the detector in such a case is equivalent to building a larger telescope. Because of the gain in power the new detector can pay for itself in a few nights of observing.

The general term "noise" refers to any process that contributes to errors of measurement or distortions of information. In astronomy there is an ultimate source of noise that cannot be overcome. Light is quantized in the form of photons whose arrival at any point in time and space is represented statistically by a characteristic distribution function; hence the number of photons that strike even a uniformly illuminated detector differs from area to area in a given time interval or for different time intervals in a given area. The visible effect of this photon noise is to introduce a certain granularity into any image, an effect that can obscure faint details.

Most detectors introduce additional noise of their own. In a photographic emulsion the light-sensitive particles are not distributed uniformly; they tend to clump together, producing the effect known as graininess, which hides features that are small or have a low contrast. Electronic detectors of all kinds generate noise as a result of the constant thermal agitation of their constituent atoms or molecules. These motions can sometimes give rise to spurious events that are indistinguishable from the externally caused ones that are being measured. For example, in a photomultiplier an electron will occasionally gain enough thermal energy to escape from the photoelectric surface and mimic a photoelectron ejected by an incoming photon. This thermal noise can be reduced by cooling the detector. For CCD's in astronomy, where long exposures are required, it is necessary to cool the detectors to a temperature of -100 degrees Celsius or lower.

Noise in electronic detectors also arises from the electronic components themselves. Such sources of noise are characterized in terms of equivalent photon events. One important attribute of the Texas Instruments CCD is its low noise level: the equivalent of 10 photoelectrons or less. That means the extraneous random noise introduced by the read-out process is the same as the photon noise associated with the detection of only about 100 individual photons. Although this noise level is low, it is nonetheless significant in astronomical applications, where the interval between the arrival of individual photons from the same object may be measured in seconds or more.

The dynamic range of a light detector is the ratio of the maximum detectable light intensity to the minimum detectable light intensity. The minimum level is usually determined by noise, the maximum by the fact that most detectors "saturate" in some way at high exposure levels. An ample dynamic range is needed for measuring faint objects near bright ones. That is a common situation in astronomy: bright stars and faint stars are scattered together throughout the sky; in quasars and most galaxies the nucleus is much brighter than the outer regions; faint spectra are "contaminated" by bright emission lines caused by artificial lights and the natural airglow (the faint light emitted by certain molecules in the earth's atmosphere). By increasing the dynamic range of a detector more photons can be collected before saturation, the relative noise due to statistical photon processes can be reduced and fainter objects can be detected.

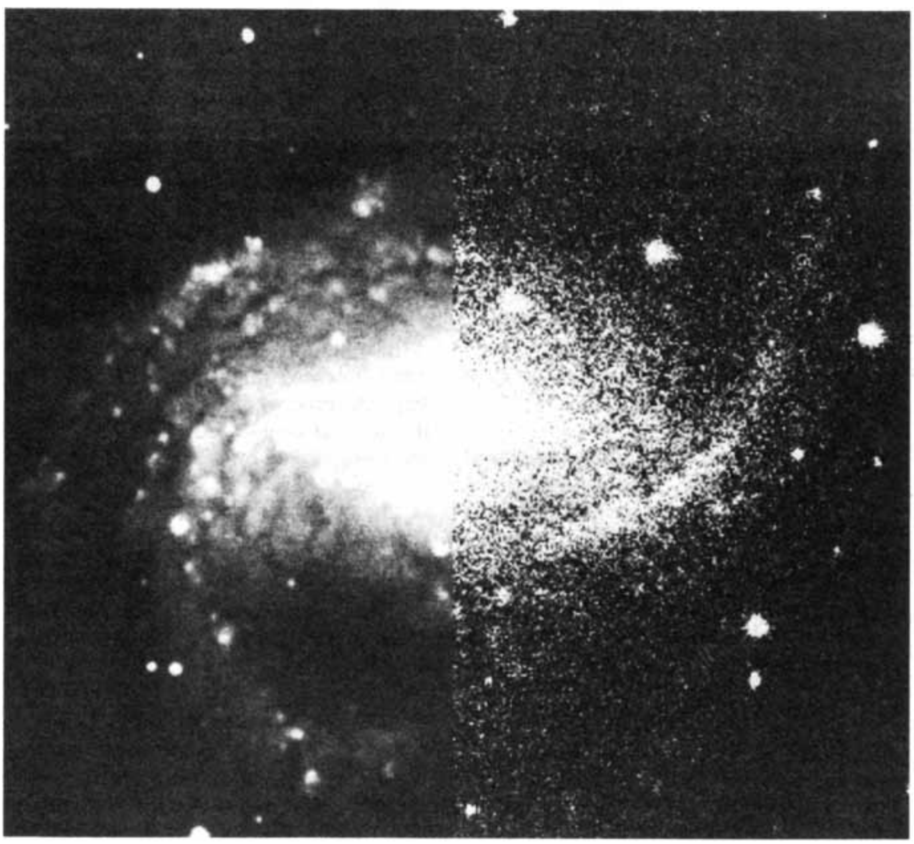
In a CCD imager the upper limit of the dynamic range is established by the filling of the potential wells with electrons. The Texas Instruments CCD has a dynamic range of about 5,000. In comparison, the dynamic range of a photographic plate or a television system is typically less than 100.

Photometric accuracy refers to the ability of a light detector to measure the exact brightness of an object. This factor becomes more important in astronomy as a particular study evolves from the stage of observing, reporting and classifying to the stage of attempting to understand the physical processes operating in the object being observed. Astrophysical theories, if they are to be most useful, must provide quantitative predictions, and the observations employed to test the theories must be accurate enough to decide between competing predictions.

An accurate measurement of brightness requires that the detector respond in a known and reproducible manner, so that a given light input always yields the same output. One can then measure the brightness of an unfamiliar object by comparing it with a source of known brightness. Furthermore, in practice it is helpful if the detector's response is linear, or directly proportional to the input, since such a relation greatly simplifies the task of analyzing the data.

The CCD imagers, like photomultipliers and many of the new television-type detectors, are linear devices. Photographs, on the other hand, are inherently nonlinear in several ways. Moreover, photographic plates can be used only once, and their characteristics are not reproducible, even for plates from the same batch of photographic emulsion, so that for the highest attainable photometric accuracy each plate must be individually calibrated, a laborious process and one that is itself not very accurate.

Geometric stability refers to the ability of a detector to record exactly where in the sky a given object is. Objects such as quasars and pulsars are often discovered solely by the radio waves they emit; on the basis of the radio emission their position in the sky can often be determined to an accuracy of a fraction of a second of arc. To identify such a radio source with a visible object in what might be a crowded field of stars calls for a light detector with a geometric accuracy at least as high. In general the geometric stability of photographic plates is quite good, whereas that of some of the new television-type detectors is rather poor. The CCD imagers have exceptionally good geometric properties, since the individual picture elements are defined by the physical structure of the chip.



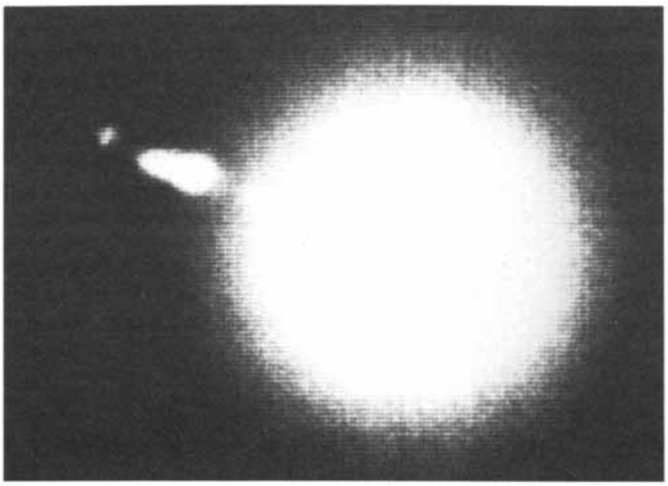
EFFECT OF NOISE on a CCD image is demonstrated in this mosaic picture of the bright spiral galaxy NGC 6951. The clarity of the original short-exposure image (*left*) is limited by "photon noise" (that is, random fluctuations in the number of photons striking the detector). In the right half of the picture the noise level of the original image has been artificially increased by computer processing but the image is otherwise unchanged. The most obvious effect of the added noise is an appearance of increased granularity. On closer inspection the loss of information in the altered image is evident in the reduced visibility of fine details and of low-contrast features such as H II (ionized hydrogen) regions and dust lanes in the galaxy's spiral arms.

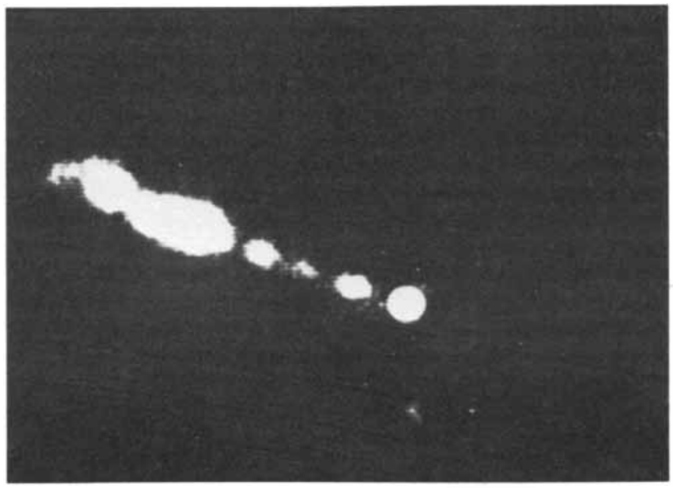
The first astronomical pictures recorded with the Texas Instruments CCD were planetary exposures made in 1976 with the 61-inch telescope on Mount Lemmon operated by the Steward Observatory of the University of Arizona. In 1977 one of the early Texas Instruments detectors was tested with the 200-inch Hale telescope on Palomar Mountain, with support from the National Science Foundation. The excellent results obtained from this early work led to the proposal to include a CCD imaging system in the Space Telescope, the 94-inch astronomical instrument scheduled to be put into orbit on a Space Shuttle flight in 1985 [see "The Space Telescope," by John N. Bahcall and Lyman Spitzer, Jr.; SCIENTIFIC AMERICAN, July].

The construction of the CCD camera for the Space Telescope is well under way at the Jet Propulsion Laboratory under the direction of a group of astronomers headed by James A. Westphal of Cal Tech. The development of this highly sophisticated detector has benefited greatly from the close interaction of detector designers, engineers and astronomers. Observations with the CCD imager have now been made at other observatories and have led to improvements in the performance of the device.

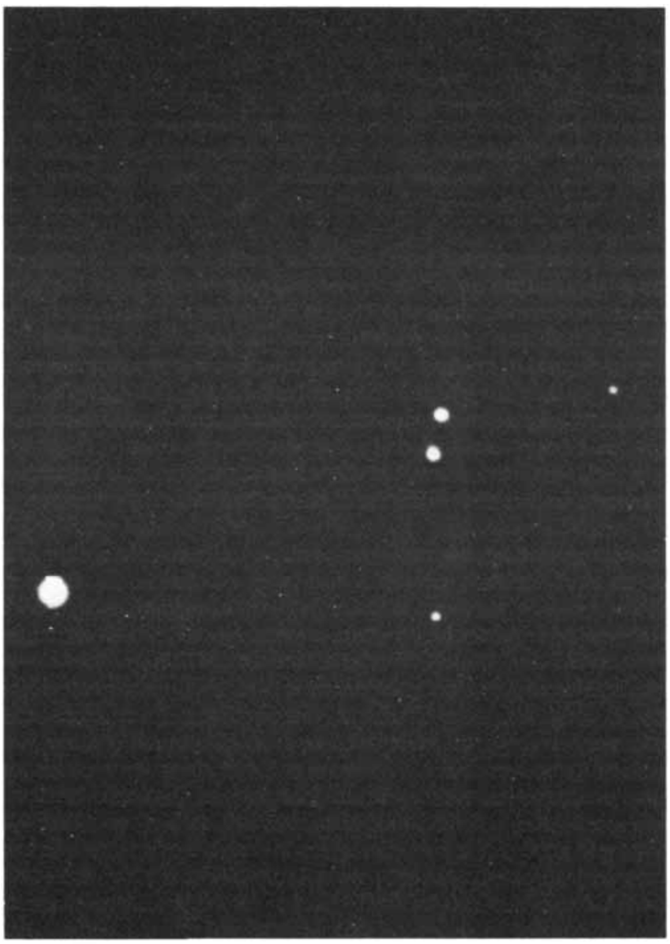
In the process of testing the new detector important data have been obtained on a wide range of astronomical topics, from planets to quasars. Some of the results of the early work accompany this article. For example, a CCD imager has been used to study the active galaxy M87 and has led to the suggestion that its nucleus harbors a massive black hole [*see top illustration on opposite page*]. Moreover, the galaxy that forms the first known gravitational lens was discovered with a CCD imager [*see bottom illustration on opposite page*].

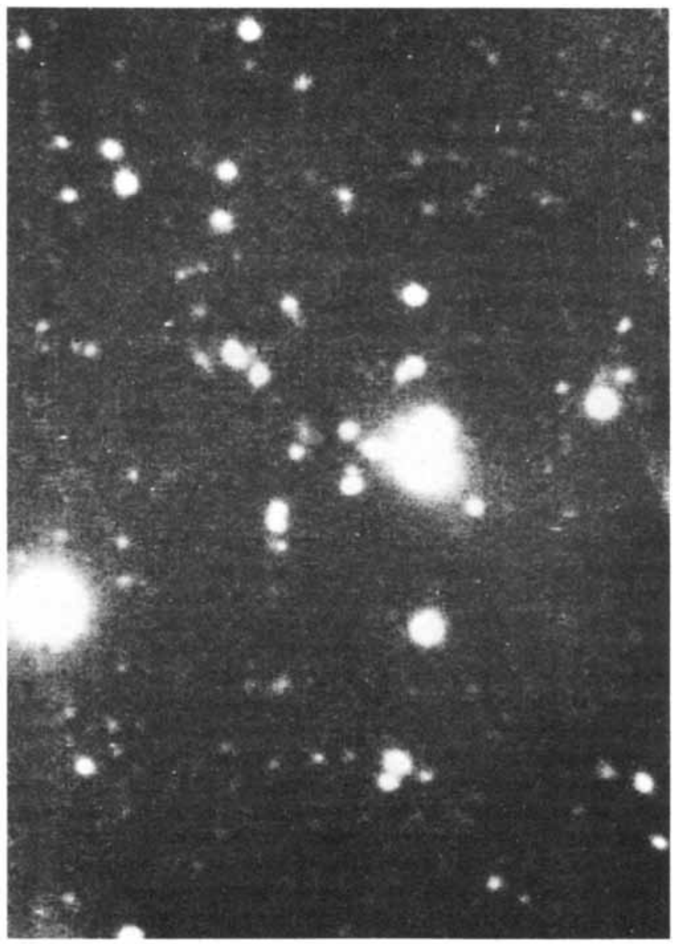
At present earth-based telescopes equipped with CCD's are being used to carry out a survey of selected small areas of the sky to detect objects fainter than the 25th magnitude: some 50 times fainter than the photographic limit of the 200-inch telescope. Red-shifted spectral lines attributable to the high recession velocities of very faint and distant galaxies and quasars are being measured. CCD imagers have been used to study the galaxies in which at least some quasars appear to be embedded, and to discover faint galaxies near some qua-





GIANT ELLIPTICAL GALAXY, M87 in the Messier catalogue of extended celestial objects, has been studied with the aid of the CCD imager in an effort to understand the nature of the violent event that is evidently taking place in its nucleus. M87 is a member of the nearest great cluster of galaxies, situated in the constellation Virgo at a distance of some 60 million light-years. In addition to being one of the brightest galaxies known M87 is a source of both radio waves and X rays. Its most peculiar feature is a jetlike series of bright spots reaching out 7,000 light-years from its center. In the CCD image at the left the outer part of the jet can be seen extending beyond the main body of the galaxy. In the CCD image at the right, made from the same data, the light from the galaxy has been removed by computer processing to show only the jet and the nucleus of the galaxy. The light from the jet, which is thought to be produced by the spiraling of energetic electrons in a magnetic field, is much bluer than the light from the normal stars that make up the rest of the galaxy. It has been suggested that the nucleus of M87 harbors a massive black hole that supplies the energy needed to account for the X-ray and radio emission from the galaxy and the radiation from the jet. CCD image was made with the 200-inch Hale telescope on Palomar Mountain.





FIRST KNOWN GRAVITATIONAL LENS was identified with the aid of this pair of photographs, both of which were reproduced from a single CCD frame recorded with the 200-inch Hale telescope on Palomar Mountain. The two photographic exposures show exactly the same region of the sky. The two bright objects at the center of the shorter exposure (*left*) originally appeared to be a pair of quasars designated Q0957 + 056; they are only six seconds of arc apart, and they have identical spectral properties. They are now known to be duplicate images of a single quasar, caused by the focusing of its light by an intervening galaxy. In the longer exposure (*right*) the lens galaxy can be seen as a fuzzy, elliptical image that completely blots out the lower image of the quasar and part of the upper image as well. This picture, which records objects fainter than 25th magnitude, is one of the deepest astronomical pictures that has ever been made.

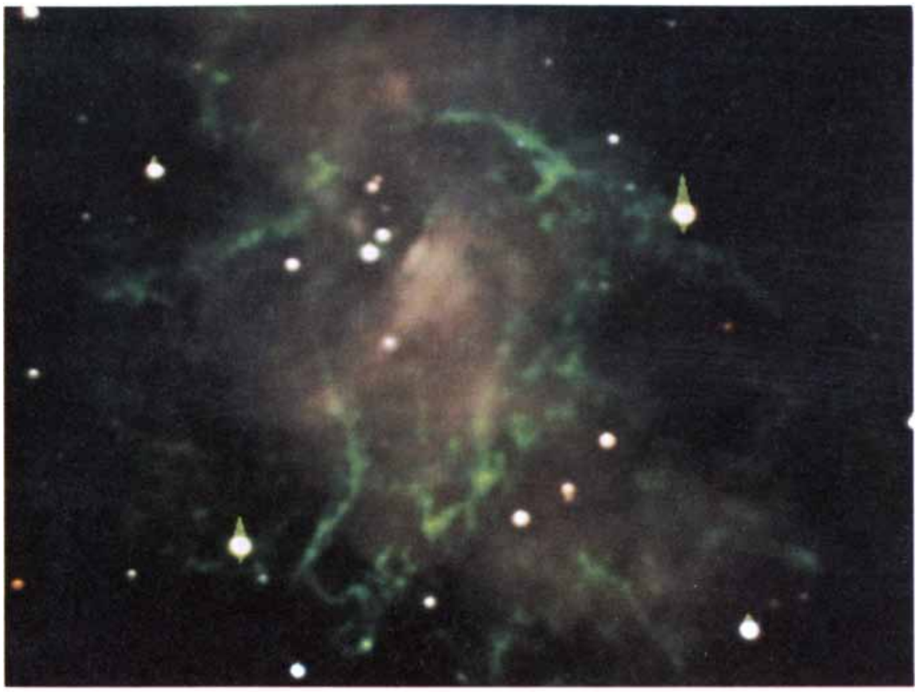
sars. They have also played an important role in studies of the evolution of stars in galaxies other than our own and in analyses of the recently discovered rings of Jupiter. As these examples indicate, the new detectors are already serving in the study of a great range of objects and problems.

The new detectors generate enormous amounts of data, and their use would be quite limited if it were not for concurrent advances in computer technology. A single picture made by a CCD imager 500 pixels on a side holds the same amount of raw information as a 100,000-word book, and a single night's observing can yield as many as 100 such pictures—the equivalent of an encyclopedia! In order to be of any value to the astronomer these data must be stored, calibrated and analyzed, and the information of interest must be extracted and presented to him in a timely and comprehensible form. It would be next to impossible to do this without a modern digital computer. Computing is already a major activity at most astronomical observatories, and it will surely become much more important as the new detectors become widely available.

CCD detectors are not perfect, and they will not totally supplant other astronomical light detectors. The main disadvantage of the CCD imager at present is its small size, which is not likely soon to exceed a few million pixels in the space of a few square centimeters. In comparison, the 100-inch du Pont telescope at the Las Campanas Observatory in Chile makes photographs on plates that are 20 inches on a side: 4,500 times larger than the largest available CCD. Although the CCD chip is simple and rugged, it takes considerable technical skill and capital investment to assemble the electronic equipment needed to collect data from a telescope with a CCD, to say nothing of the computer power needed to wring scientifically interesting results from the data.

Furthermore, there are many problems in astronomy for which the attributes of a CCD imager are simply not needed, or for which its limitations make it unsuitable. For example, for surveys of large areas of the sky in which extreme accuracy and the capability of detecting very faint objects are not needed, it is doubtful that anything will soon replace photographic plates, with their unique combination of simplicity, low cost and ease of handling, storage and reproduction.

Nevertheless, the new detectors are a powerful addition to the astronomer's tools. They have already proved their value in solving difficult astronomical problems, and as they become more available they will help to solve some of the many fascinating problems with which modern astronomy is blessed.



CRAB NEBULA is seen in this CCD-based composite photograph as two components: (1) a network of gaseous filaments (which appear here as green) radiating at a set of discrete wavelengths characteristic of the emission from a hot gas and (2) a continuous emission characteristic of the radiation produced by the spiraling of energetic electrons in a magnetic field. Energy is being supplied to the nebula by a pulsar at its center. The pulsar, the first of its kind observed at wavelengths other than those in the radio region of the spectrum, is thought to be a superdense neutron star spinning at the rate of 30 revolutions per second. The pulsar is the remains of a star that exploded in A.D. 1054 as a supernova and the nebula is the debris from the explosion. The false-color composite was made at the Jet Propulsion Laboratory of Cal Tech by combining the data from three CCD frames, which were made originally at the 200-inch telescope through green, red and infrared filters. Since the eye is not sensitive to infrared radiation, the CCD frames were reproduced on the photographic film through blue, green and red filters, with the result that the picture has been "blue-shifted" by one color band. Hence the filaments, which appear green, are actually red, because the strongest of their emission lines lie in the red.

PLANETARY NEBULA, the well-known Ring Nebula in Lyra, is an expanding shell of gas ejected from the star visible at the center. The gas shines by fluorescence: it absorbs ultraviolet radiation from the hot central star and reradiates it at visible wavelengths. In this two-color, CCD-based composite photograph the nebula appears green on the inside and red on the outside because the higher-energy photons from the star are absorbed closer to the center and heat the gas there to a higher temperature, exciting shorter-wavelength (greener) emission.