Low Light Level Detectors for Astronomy

Many types are available but successful use does not depend solely upon detector performance.

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From earliest times man has sought to improve his ability to observe and record the brightnesses, positions, and motions of the celestial objects. The connection between improvement of observational capability and advances in the science of astronomy is a strong one. Even before Galileo's first use of the telescope, the Danish astronomer, Tycho Brahe, built the largest observatory of his time. His accurate measures of the positions of the planets over an extended period of time formed the basis for Johannes Kepler's development of the laws of planetary motion. Many subsequent discoveries can be directly related to the use of improved instrumentation. The proof that the wispy smudges seen between the stars are actually distant galaxies composed of billions of stars depended almost completely on the use of the 100-inch (1 inch = 2.54 centimeters) telescope at Mt. Wilson. The 200-inch telescope on Palomar has likewise been central to many advances in our knowledge of the universe.

Almost all the information we have about stars, galaxies, nebulas, and other celestial objects comes to us in the form of photons. Physical characteristics such as density, temperature, and composition must be determined indirectly by analyzing the electromagnetic radiation arriving at the earth from these objects. Most astronomical objects are very faint by normal standards. Even at the focus of large telescopes, photons from the faintest measurable stars arrive at the rate of a few per second. The detectors used to record these photons form an important part of astronomical instrumentation. This article summarizes the detectors that are now in use at astronomical observatories and provides references to their detailed operating characteristics.

The Photographic Plate

Since the advent of photography in the second half of the last century, astronomers have used the photographic plate to detect and record images at the focal plane of their telescopes. Despite its drawbacks, the photographic plate is a wonderful device for recording a large amount of information. A large astronomical plate typically contains 10^8 or more individual picture elements otherwise known as pixels. Yet the pictorial presentation inherent in a photograph conveys this information to the human brain in a very effective manner. The photographic plate also has the capability of integrating over long exposure times thus greatly extending the astronomer's ability to detect faint objects. Moreover, photography is relatively easy to use and, with care, the stored record is permanent.

Nevertheless the photographic plate has serious drawbacks as a photometric measure. These include nonlinear response, limited dynamic range, reciprocity failure (the reduction in sensitivity as exposure time is increased), adjacency effects (nonindependence of adjacent pixels), low quantum efficiency, and relatively high granularity. Many of the nonlinear effects are also wavelength dependent, and special processing methods are needed if the uniformity of response across the plate is to be maintained. These qualities make it difficult to calibrate a photographic plate well enough to achieve a photometric accuracy better than 10 percent (*1*). It is impossible to give a single number for the real sensitivity of photographic plates because the quantum efficiency depends on the exposure time. But in any case, the effective quantum efficiency of the older astronomical plates under normal use was no greater than 1 percent and usually less (*2*).

Within the past 10 years, new spectroscopic emulsions with considerable improvement in sensitivity and granularity have become available. New pre-exposure sensitizing techniques have been developed; these include baking at 60°C, soaking in nitrogen, soaking in hydrogen, preflashing with a controlled light, or a combination of these. The effectiveness of the photographic plate as a device to detect and record photons has improved considerably over the past 15 years (*3, 4*). While perhaps not as glamorous as the use of television-type sensors, the effect of these recent improvements on astronomical research has been enormous.

In seeking ways to measure fainter objects, it was natural for astronomers to turn to the use of the photocathode. The lure of the "perfect detector" has been a strong force influencing the development of astronomical instrumentation during the last 25 years. The desired characteristics are easy to enumerate; high quantum efficiency over a wide range of wavelengths, linearity of response, large dynamic range, both large- and small-scale uniformity of response across the surface of the detector, complete independence of response for neighboring pixels, freedom from detector-generated noise, and the ability to record images with good spatial resolution. This is quite an imposing list of requirements, not all of which have always been appreciated. One requirement that is often overlooked by enthusiastic instrument developers is simplicity of use and reliability over extended periods at the telescope. The ultimate test of a new detector is not the pictoral quality of its first images but the new knowledge ultimately derived from its use by a wide range of working astronomers. In one or two cases where sufficient resources have been available, it has been possible to use a very complicated detector in a relatively routine manner. But the most useful scientific tool continues to be that one which can be used by a large number of scientists without the need for a long or complicated introduction or training period.

The photocathode with its 10- to 20-fold improvement in quantum efficiency over the photographic plate was naturally of great interest to astronomers. Early astronomical use of the photomultiplier tube (a 1-pixel detector) demonstrated the many advantages of using a photocathode; good quantum efficiency, linearity, and relative ease of calibration. Together these attributes make it possible to make routine measurements with an error smaller than 1 percent.

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Two-Dimensional Detectors with the Use of Photocathodes

To go to full two-dimensional imaging with a photocathode, two methods were tried. The most scientifically productive method for astronomical imaging has been the use of image-intensifier tubes. The cathode converts photons to photoelectrons and a system of electron optics focuses the image onto a phosphor screen at the output. A photographic plate then records the resulting image. The speed gain of the cathode is realized, especially in the infrared, and the severe nonlinearity of the photographic response at the lowest light levels is avoided, making the output easier to calibrate. These gains are achieved at the cost of some image degradation. Astronomical applications of image-intensifier tubes have been reviewed by Wampler and Ford (*5*) and are included in Livingston's review (*6*). The situation has not changed much since the later review, except that fiber-optic faceplates to couple the cathode and the phosphor to the outside in electrostatically focused tubes are in some cases now being made of ultraviolet transmitting glass (*7*). The importance of the intensifier lies not only in its widespread use by astronomers throughout the world, but also in the fact that many of the other detector systems in use today depend on one or more stages of intensification for their operation.

The use of television-type sensors is one way to apply photocathodes to astronomical use. Conventional television camera tubes, such as vidicons and orthicons, have not performed well under the high-accuracy, low-noise requirements of astronomy. The SEC (secondary electron conduction) vidicon effectively has one stage of intensification and also the capability to integrate for an hour or more. This brings the signal up to a level sufficient to overcome the inherent noise of the readout process, which amounts to several hundred electrons. Although it can be made in a rather large format (50 by 50 millimeters), the SEC vidicon has a limited dynamic range and nonlinear characteristics. However, several groups have successfully used this detector for a few specific projects (*8*).

A breakthrough of sorts in the use of television-type sensors came in 1971 with the introduction of a vidicon tube having a solid-state diode array as the target. Livingston (*6*) has summarized the early use of both the silicon vidicon and the silicon intensified target (SIT) vidicon. In the first tube the diode array is the photosensitive target. The spectral response extends out to a wavelength of 1 micrometer; but with no predetection amplification, the signal at low light levels is swamped by the readout noise of several hundred electrons. This tube has been used extensively by McCord and his co-workers especially for planetary observations. With extreme care they have achieved accuracies of better than 1 percent for photometry of bright objects (*9*). As in any system in which television-type sweep circuits are used for readout, extreme care must be taken to maintain geometric stability of the sweep. This is especially true if successive pictures are to be subtracted or divided to find color or polarization differences. Shifts of as little as one-tenth of a pixel can cause problems if the image contains extreme gradients such as those found in a star field.

The SIT vidicon uses a photocathode and one stage of intensification to overcome the readout noise limitation. Each photoelectron released from the cathode generates approximately 2000 electrons in the silicon target. The resulting signal is essentially free from readout noise. The SIT vidicon has been rather successful from the scientific standpoint. It is used on a regular basis at several observatories (*7*) and has been used in the past 3 years to measure the red shifts on more than 100 of the most distant (and faint) galaxies known (*10*).

A third way to utilize the photocathode in a direct way is to record the photoelectrons directly on photographic film, a process named electronography. Originally developed almost single-handedly by Professor A. Lallemand in Paris, electronography has been used in the United States by Walker at Lick Observatory, who has recently prepared an eloquent summary of the history of electronography (*11*). In the simplest electronographic camera, the film is exposed directly to the photocathode in a vacuum. An electron optic system focuses the photoelectrons directly onto the film. At the conclusion of each series of exposures, the film is removed, thereby destroying the cathode. A new cathode must be made each time the camera is used—which is a severe drawback.

Kron has developed an electronographic camera with a vacuum valve which allows the cathode to be used many times (*12*). After the film chamber is evacuated and cooled the valve is opened for the exposure sequence. It is closed again for film removal. The operation is somewhat less complicated than that of the Lallemand camera, but in practice the user of the Kron camera must still make his own cathodes.

A third method of electronography involves the use of a thin mica window through which the photoelectrons penetrate, striking the recording film that is pressed against the window. The difficulty comes in trying to maintain the film tightly against the 5-micrometer-thick mica window, which must also withstand the atmospheric pressure. So far this has limited the available size of the detector (5 by 30 millimeters), although larger formats now seem possible.

Despite high quantum efficiency, good linearity, high dynamic range, and exceptional spatial resolution, the electronographic detectors have not really fulfilled the early hope that they would become a universal detector for astronomical purposes. The reason is that electronography is doubly complicated. First, the camera itself is difficult to use. Then, the results are recorded on film and, although the nuclear emulsions used in electronography are linear, the problem of extracting the information from the film is far from trivial (*13*). Electronography does not conform to the requirement for simplicity set down earlier in this article (*14*).

Composite Detector Systems

Perhaps the most successful modern astronomical detector, the one that sets the standard by which others are judged, is the Image Dissector Scanner developed by Wampler and Robinson at Lick Observatory (*15*). In the 6 years since its inception, this detector has been used extensively at Lick Observatory by staff and visitors alike. It has been copied at Ohio State, Texas, Kitt Peak National Observatory, and in Australia. It is almost universally known as the "Wampler scanner." To understand the success of this device, one has to be aware of two things. The first is the central role in astronomy played by spectroscopic observations, and the second is the extent to which prime observing sites of 25 years ago have been compromised by the increasing brightness of the night sky caused by scattered light originating from growing urban areas.

So far the Wampler scanner is a spectroscopic or one-dimensional detector. In operation it has three stages of intensification followed by an image-dissector tube scanning the output phosphor of the last intensifier. The scanning format is two lines each 2048 pixels long. The signal from the dissector is digitized and added synchronously in a circulating memory. The persistence of the phosphor in the intensifier serves to store the signal until it can be read by the dissector tube. In use, one line contains the spectrum of the object plus the night sky, while the second line contains the spectrum of the night sky alone taken at the same time. The effects of the bright night sky can be nearly eliminated by simple subtraction and the astronomer can obtain spectra of objects much fainter than the night sky. In addition, the digital data is continuously displayed graphically at the telescope so the astronomer has a check on the operation of the instrument. A minicomputer controls the operation of the detector which adds to the ease and simplicity of use.

The Wampler scanner suffers from two problems—an increase in background caused by electron scattering within the image-dissector tube, and long decay times for the phosphor which limits brightness of objects observed. Faint objects cannot be observed after bright ones. The latter problem can be alleviated by careful planning of the observing sequence (*16*). The noise introduced by the intensifier chain degrades the system by a factor of 2 compared to the ideal photon noise limited case.

The Wampler scanner is a limited instrument, put together in 1970 as a stopgap until a better detector was developed. The continued success of this system emphasizes the point that reliability and ease of use (including capacity for data handling and analysis) must be considered in developing a detector system. By limiting the detector to one dimension, many problems have been minimized and the data analysis problem can be handled with an inexpensive minicomputer plus a simple graphics display. The Lick Observatory system has facilitated the entire process of extracting scientific data from starlight.

A possible ideal detector would respond to every photoelectron generated by the cathode, putting out a pulse for each one. Each pulse would be position-coded, and these would be accumulated in an appropriate memory. Two such two-dimensional detectors have been built for astronomical purposes. The original pulse-counting detector was assembled by Boksenberg of University College, London (*17*). A similar device is still under development by Gilbert at the University of Arizona (*18*). Both systems are complicated in operation. They both have several stages of intensification followed by a television-type camera tube. Both systems employ electronics packages which accurately locate the centroid of the intensified pulse which has been degraded by the intensifier chain. Development of both systems has been long and relatively expensive. To date, the major use of Boksenberg's system has been in the one-dimensional mode for spectroscopy of faint objects. The crucial limitation in a pulse-counting instrument is the requirement to sample each pixel more often than the photon arrival rate. As the number of pixels increases the speed of the electronics limits the photoelectron counting rate. Ten events per second per pixel seems to be a reasonable upper limit. At this rate an accurate calibration requires a long exposure time to accumulate sufficient events so that the random noise, which varies as the square root of the number of events, becomes acceptably small. Other operational problems are brought on by the inability to observe bright objects, since the stars generally used as calibration objects are all too bright to be observed with this detector. Nevertheless Boksenberg has shown that, given sufficient support, it is possible to make such a complicated system work successfully at the telescope.

An active program of spectroscopy of faint objects has been carried out with this detector at the Palomar 200-inch and other telescopes (*19*).

Solid-State Diode Arrays

The development of arrays of silicon diodes is a natural outgrowth of the increasing technological capability of semiconductor manufacturers. Various photosensitive silicon diode arrays have been available for several years. The integrated linear diode arrays manufactured by Reticon were among the first available and have been used as astronomical detectors in a number of applications (*20*). They are geometrically stable, relatively simple to use, have a high resistive quantum efficiency (RQE) (*21*), good dynamic range, and almost complete freedom from cross talk between adjacent elements (*22*). Switches to read out the charge accumulated in each diode during the exposure are built into the chip along with a shift register for clocking. During the readout the charge accumulated in the diodes appears as a video signal on the output lines and is measured by a charge-integrating amplifier. A fixed pattern of noise which exists on the readout lines is caused by switching transients. This noise is troublesome but can be removed by subtracting a "dark" frame taken immediately after the exposure. The fixed pattern noise is sufficiently stable that complete cancellation is possible, down to the limit of the amplifier noise. For a Reticon this limit is equivalent to about 1000 electrons per pixel, which limits the use of the Reticon to relatively bright objects or the use of long integration times. Random thermal noise during the exposure can be reduced to the equivalent of 1 electron per second per diode at a temperature of $-130°C$. Exposures of up to 3 hours in length have been made by Tull (*23*). It has been shown by Geary that the Reticon is best used for spectroscopy of relatively bright sources where high photometric precision is desired (*24*). For instance, Tull (*23*) has reported recent measurements of stellar spectra in which the signal-to-noise ratio exceeds 1000.

The Reticon has one other advantage. The pixels have been optimized for spectroscopy. One especially useful chip contains two parallel arrays of 936 elements each. The pixels are 375 micrometers long and 30 micrometers wide spaced on 30-micrometer centers. This geometry matches well to a spectrograph slit and allows simultaneous spectra to be taken of adjacent areas for subtraction of the night sky spectrum as described above.

A number of other detectors are being developed that employ one or more stages of intensification ahead of a Reticon array. They range from a very light and compact detector developed at Wisconsin (*25*) to far larger and more complicated pulse-counting devices. The Wisconsin detector uses a microchannel plate as the intensifier coupled to the Reticon by fiber optics. The reported performance is very good with excellent linearity and a high dynamic range.

Shectman at the Hale Observatories and Hiltner at the University of Michigan have developed a pulse-counting spectroscopic detector using six stages of intensification and a Reticon array (*26*). They use a very clever and simple scheme to locate the centroid of the pulse produced at the output of the last intensifier. So despite the large width of the output pulse, there is no loss of effective resolution through the intensification process. This simple and relatively inexpensive detector competes very favorably with the other pulse-counting detectors described earlier.

Another successful detector named the Digicon uses the Reticon in the electron-bombarded mode to detect photoelectrons directly (*27*). A remotely processed cathode and the Reticon are assembled together in an evacuated tube body. In use the photoelectrons from the cathode are accelerated and focused on the Reticon. Each photoelectron generates 5000 electrons and the resulting charge is read out in the usual manner. Even at low light levels the readout noise is much less than the signal, and the noise is close to that of the input photons.

The Digicon has two variants. One uses the Reticon self-scanned array. The other, originally developed by Beaver and McIlwain (*28*), contains a diode array with discrete amplifiers. Both versions of the Digicon have been enthusiastically accepted by the working astronomers who have used them. The original version with 40 pixels has been in use since 1971. Newer models have linear arrays of 200 pixels. Some problems have recently come up in the manufacture of the self-scanned version of the Digicon, but they seem to have been solved (*29*).

So far I have discussed only the linear diode arrays. There are two types of two-dimensional diode arrays now in use. One is the charge-injection device (CID) and the other is the charge-coupled device (CCD). They differ mainly in the way the accumulated charge is read out. In the CID, manipulation of row and column charges allows random access to the individual pixels if desired. The interesting feature is that the charge in each pixel can be read nondestructively. By rereading a number of times, it is possible to reduce the readout noise, which has been reported to be equivalent to about 400 electrons, to a much lower value (*22*). It is not yet clear how far this technique can be pushed, or how aggressively the CID technology will be pressed by the commercial manufacturers.

The CCD array is read out by transferring charge from one pixel to the next until the entire array has been read out. Several groups in the United States attempted to use the early CCD arrays of 100 by 100 pixels but without great success. In the early devices the readout noise limited use to relatively bright objects.

A relatively recent development has drastically changed that picture. In the last 6 months Texas Instruments has developed a pixel CCD detector (400 by 400 pixels) in which the silicon chip is thinned to a 10-micrometer thickness and illuminated from the reverse side. In tests at the Jet Propulsion Laboratory (*30*), the special on-chip amplifier has actually achieved a readout noise of only 15 electrons per pixel. The new CCD also has excellent linearity, a dynamic range in excess of 10,000, a peak RQE of 70 percent at a wavelength of 0.7 micrometer, and a reasonable sensitivity over the range 0.4 micrometer to 1.1 micrometers. Westphal at the California Institute of Technology is experimenting with a very promising method to extend the sensitivity well into the ultraviolet.

Early use at the telescope indicates that this new CCD is performing as well under actual observing conditions as it did in the laboratory. If the CCD development program continues as expected, we may see CCD detectors (800 by 800 pixels) with the same characteristics within a year. Such a detector would come close to answering most of the detector needs of ground-based astronomers. In particular, the low readout means that intensification is no longer necessary, even at the very lowest light levels.

Summary

There is an almost bewildering variety of detectors being used for ground-based astronomical observations. Many of the detectors have advantages for particular projects. One-dimensional detectors are simple, yet suitable for spectroscopy. Other detectors offer high photometric precision and dimensional stability. Some are designed for observing only faint objects and some for bright ones. Sometimes the necessity of having a high quantum efficiency at a particular wavelength dictates the choice of detector.

In reality the situation is even more chaotic. This review has not covered some of the exotic detectors that have been developed for x-ray and far-ultraviolet imaging from spacecraft. These detectors use devices such as resistive plates, multianode or crossed-wire microchannel plates, and so on. These devices have not yet seen extensive use in ground-based applications, and their future as visible light detectors remains uncertain.

The reasons for the development of such a wide variety of detectors are clear. Commercially available devices are simply not capable of meeting the low light level and photometric performance capabilities needed for astronomical observations. The driving forces are the commercial and military applications for detectors, and with few exceptions there has not been sufficient funding available to mount a detector development program for astronomy. Therefore, astronomers have sought to adapt existing commercial devices to the particular problem at hand. The large number of individual efforts summarized in this review is the result.

In the future, I expect the variety to diminish as one or two really good detectors become capable of performing well under the wide variety of observational conditions encountered in astronomy. Many people have proclaimed the ultimate detector to be just around the corner. This is yet to happen. However, I venture to speculate that low-noise, high-performance CCD detectors with a format of 500 by 500 or larger will emerge as the preferred astronomical detector within the next few years. I also expect photographic plates will continue to be used for the many applications requiring wide fields up to 10,000 pixels on a side. Finally, as the detectors approach the ultimate quantum limit, attention will shift away from them and toward development of the system necessary to manipulate, display, and extract the information from the 250,000 numbers that make up a 500 by 500 digital image.

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