Low-light-level charge-coupled device imaging in astronomy

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Charge-coupled devices (CCD's) on both large and small telescopes are revolutionizing astronomy, permitting studies to be made of objects up to 10 times fainter than possible by using photographic and video camera techniques. This is due both to the high quantum efficiency and to the photometric stability of the CCD. Chopping techniques, taking advantage of this stability, permit cancellation of low-level systematics. Faint galaxies and stars of 27-V magnitude are detected in 2-h integration on a 4-m telescope, corresponding to 0.02 (photons/sec)/pixel. Automated image preprocessing and pattern recognition at high data rates permit statistical studies to be made of multispectral CCD data. In the future the efficiency of large telescopes for survey studies will be improved by the use of CCD mosaics covering the entire usable focal plane.

INTRODUCTION

The history of astronomy is, in large part, dominated by the history of detector development. As detector technology progressed from the unaided eye to visual telescopes, to photographic emulsions, and to photoelectric systems, each improvement brought with it answers to old questions as well as a host of new questions and the discovery of new types of objects. In astronomy, as in particle physics, progress is closely tied to deeper images, higher resolution, larger statistical samples, and broader spectral response, as the observer effectively opens his eyes wider to the view offered by the universe.

The remarkable improvement in detector sensitivity during the past century—from early emulsions to charge-coupled devices (CCD's)—is sketched in Fig. 1. The flux from the faintest galaxies detected in optical surveys is plotted as a function of time. In the CCD camera the astronomer now has at his disposal an instrument whose sensitivity is limited primarily by quantum mechanics and the nature of our atmosphere. Perhaps the most significant gains are now being made in faint-object spectroscopy. For years it has been relatively easy to record images of faint galaxies and stars for which adequate spectra, at a few angstroms' resolution, were beyond the reach of the largest telescopes. The recent reduction in CCD readout noise and the virtual elimination of low-level systematics in CCD's has raised the throughput of spectrographs from less than 1 to more than 10%. Further significant improvements in sensitivity can be attained only by the construction of larger-aperture telescopes.

While the observer of small objects has in the CCD camera a device nearly optimum in terms of sensitivity and response, this happy state of affairs does not extend to wide-field photometry and to statistical or survey observations. Currently available CCD's are small and cover only about 1% of the good image area at the prime focus of typical large telescopes. The statistical astronomer simply cannot afford to waste 99% of the image and is thus forced to rely on photographic emulsions for the detector. The price paid for wider coverage is high: In comparison with CCD cameras, the photographic plate is seriously inadequate in sensitivity, wavelength response, reproducibility, dynamic range, and linearity.

Much of modern optical and infrared (IR) astronomy is photon starved. That is, to pursue current research in imaging and spectroscopy, it is often necessary to integrate longer than several nights for sufficient signal-to-noise ratio. Yet for such long integrations there are diminishing returns: Low-level systematic error because of weather (night-sky variations, clouds, etc.) limits the accuracy of photometry. Thus this fractional error in night-sky brightness translates into a limiting faintness for surface photometry of galaxies. Even worse, there are limiting upper-atmosphere-generated systematics on the detector itself. To solve these problems, we must use the highest-quantum-efficiency detectors on the largest telescopes and develop image-acquisition and -reduction techniques that cancel the systematics.

CHARGE-COUPLED DEVICES

Following the invention of CCD's by Boyle and Smith,[1] they have been used widely as memories, delay lines, and imagers. The book by Sequin and Tompsett[2] reviews the early CCD architecture. The architecture with the maximum effective quantum efficiency is the so-called "frame-transfer" CCD. Charge in pixel wells is clocked down columns and read out (last row) through an on-chip amplifier. The presence of surface states and the resulting trapped charge in surface-channel CCD's reduces their usefulness at low light levels. A solution is to store the charge in the bulk semiconductor away from the Si–SiO_2 interface. CCD's used in low-light-level detection are buried channel and usually three phase. See Blouke *et al.*[3] for a description of a modern CCD. If the device is kept sufficiently cold, say, at 160 K, latent images may be stored for days, and the thermal phonon-induced noise is negligible in a 1-h exposure. Thermally induced dark current at 160 K is about 20 e per pixel per hour. Recent buried-channel CCD's have full wells of 10^5 e or greater and have a dynamic range of up to 10^5. The charge-transfer efficiency is now typically 0.99999 at exposure levels

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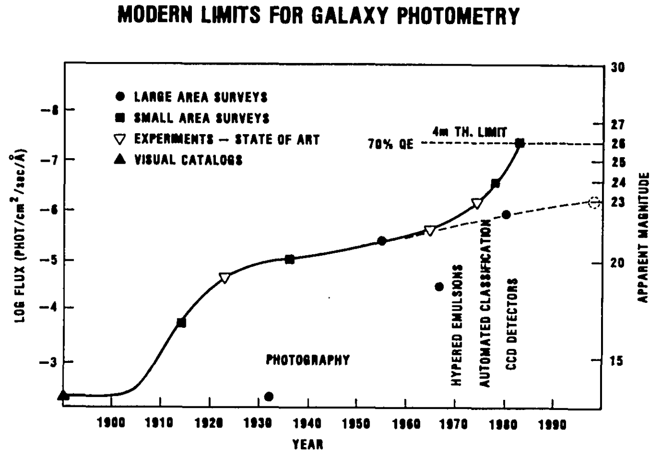


Fig. 1. The history of the faint limit of galaxy photometry has been dominated by advances in detector technology. Shown is the limiting flux in photons cm^{-2} sec^{-1} $Å^{-1}$ (and also green magnitude) as a function of time. The CCD has pushed the efficiency per detector area of telescopes to its theoretical maximum. The lower dashed line charts the large-area photographic Schmidt surveys.

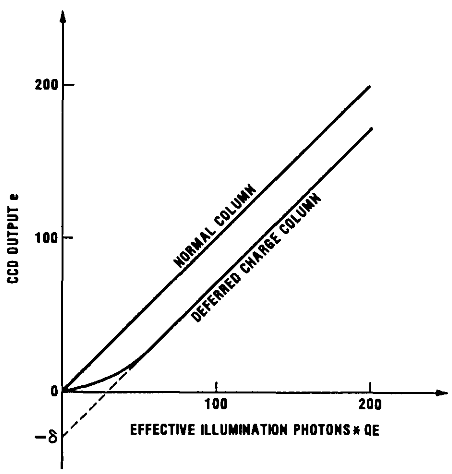


Fig. 2. The deferred charge effect at very low light levels in CCD's. Current state-of-the-art CCD's have less than 10–30-*e* deferred charge. These nonlinearities, important only in very short or spectroscopic exposures, can be reduced in image processing.

above 10–50 *e*/pixel. This deferred-charge effect is shown in Fig. 2, and it can be reduced in image processing.[4] The deferred charge or fat-zero level varies from column to column and is generally below 30 *e* in the best current CCD's. This low-level nonlinearity is of concern only in very short exposures or spectroscopic applications, in which the background in the exposure is below 100 *e*.

Characteristics of currently marketed CCD's suitable for very low-light-level work vary widely. Pixel sizes range between 15 and 30 μm. Most are front illuminated and have a readout noise less than 50 *e*. Figure 3 shows the quantum efficiency of two thinned back-illuminated CCD's. This could be improved somewhat by antireflection coating. So-called "interline transfer" CCD's have the advantage of self-shuttering but at the price of more than a factor-of-2 loss in quantum efficiency.

CCD's have revolutionized astronomy in the past 5 years, much as photographic emulsions did so 50 years ago. The gain in quantum efficiency over hypersensitized photographic plates is more than a factor of 10. Photomultiplier tubes revolutionized the field of single-object photometry and spectroscopy. The photocathode quantum efficiency of up to 20% was equivalent to an order-of-magnitude increase in the light-gathering power of the telescope. Even so, the phototube could measure only one wavelength at a time in a scanning spectrograph. The introduction of image intensifiers brought the quantum efficiency of photomultiplier tubes to imaging detectors. During the 1970's, ISIT's and similar intensified detectors were introduced into spectrographs; see Robinson and Wampler[5] and Boksenberg.[6] Good reviews are given by Ford[7] and Timothy.[8] Aside from limitations imposed by their front-end quantum efficiency, these detectors have been limited in faint-object work because of systematics: Problems with the stability and reproducibility of the detector often preclude effective chopping techniques for removal of low-level systematics in long exposures. Multiobject low-light-level spectroscopy and surveys for very faint objects had to wait for the CCD.

In cases in which images are needed more than once per 100 sec or so, CCD's have a disadvantage: A noise penalty of 10 or more electrons is paid on each read, per pixel. Thus, for speckle work where millisecond sampling is required, intensifiers (discussed elsewhere in this issue) are the only alternative. Since the signal-to-noise ratio (S/N) is determined by the first element in the detector system, the use of an intensified detector with a quantum efficiency of 4–10% results in a decrease in S/N (per exposure time) by a factor of 3–5. However, for the vast majority of applications in low-light-level imaging and spectroscopy, longer integration times are allowable, and one can take advantage of the high quantum efficiency (QE) and dimensional stability of the CCD. In many cases, 1–2-m class telescopes instrumented with CCD's are now doing the research that was possible only on the largest telescopes in the past.

Loh[9] built one of the first CCD cameras used in astronomy. The care and feeding of CCD's was reviewed by Gunn and Westphal,[10] and several good reviews of CCD's applied to astronomy appear in Vol. 331 of the *Proceedings of the Society of Photo-Optical and Instrumentation Engineers*.[11] New techniques leading to enhanced and long-term stable ultraviolet (UV) response of CCD's have been developed recently.[12,13] Unlike photographic plates, video cameras,

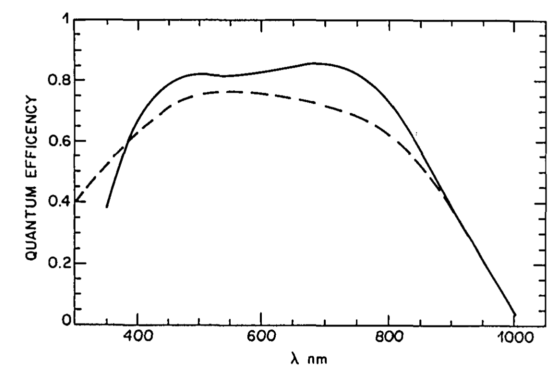


Fig. 3. The quantum efficiency of the thinned RCA CCD used in our work (solid line) and a thinned TI 800 × 800 CCD (dashed line) as a function of wavelength. Recently, CCD's have become available with enhanced UV response. In the future, CCDs with response in the IR will become available.

and intensified detectors, CCD imagers are inherently stable: each pixel in subsequent images on the same CCD is prepared in an identical way. This opens the door to chopping techniques for cancellation of systematics. Until recently, weather-related systematics in CCD imagers have prevented effective use of long integrations. Below, I briefly review techniques for faint-object photometric imaging with CCD's in astronomy. The same techniques are now being applied to CCD spectroscopy. Advances in computing technology have more than kept pace with the rapid detector development, with the result that the large volumes of data from digital imaging systems may be handled and reduced effectively. The conclusion is that astronomy is currently more limited by the size of the telescopes than by problems with the CCD detectors.

TECHNIQUES FOR LOW-LEVEL IMAGING

Thinned CCD's offer a high QE between the UV (if pretreated) and the near IR. Among their advantages are high QE, a very large dynamic range, excellent linearity, and ease of calibration. However, when one is trying to do high-S/N observations or work on faint objects very close to the night-sky level, the systematic errors tend to dominate the random errors from photon statistics. The first advance in counteracting low-level systematics in the detector was the drift-scan technique.[14–16] The CCD image is clocked down columns very slowly, as the image from the telescope is scanned along with it. This technique averages over some of the fixed pattern noise on the CCD (along one dimension) and is effective in reducing systematics to below 1% of the night-sky background level. However, precise photometry is difficult in normal conditions of changing atmospheric transmission or seeing, and other techniques must be developed to reduce systematics below a level of 0.1% of background.

I will briefly review techniques that have allowed a 4-m telescope to be pushed to its photon-noise limit in cumulative exposures lasting 6 h. S/N trade-offs permitting galaxy detection and photometry to 27th magnitude in such processed exposures were discussed by Tyson.[17] Recently techniques for data acquisition, calibration, and processing for CCD imaging in the range $400 < \lambda < 1000$ nm were developed that minimize these systematic errors and permit routine construction of images with good photometric accuracy for galaxies and stars to 27-V magnitude (with 0.2 magnitude errors) in 7000 sec on a 4-m telescope or a flux of 1.7×10^{-5} photons cm^{-2} sec^{-1} in a 100-nm bandwidth at 500 nm. The dominant sources of error are the mismatch between calibration flat fields and the actual night-sky background and, for some thinned-CCD chips, fringing that is due to unblocked night-sky emission lines. Generation of a master flat field and sky frame from the data themselves permits removal of the systematics to better than 0.03% of night sky. Sky surface-brightness errors (3σ) range from 29–27 magnitude/(sec of arc)^2 (0.6 sec of arc/pixel) for $400 < \lambda < 1000$ nm, in 100-nm bands, per 2-h exposure at $f/2.6$. This faint-object survey is being done in collaboration with Pat Seitzer (National Optical Astronomy Observatories, Tucson, Arizona).

The detector is a thinned, buried-channel, backside-illuminated CCD, 320×512 pixels.[18] Readout time is 8 sec. Analog-correlated double sampling is used before the 15-bit analog-to-digital converter. The QE of the CCD is 30% at 350 nm, 80% at 600 nm, and 35% at 900 nm. Total efficiency of the atmosphere, telescope, optics, and CCD detector system is about 52% at 600 nm. Readout noise and systematics on a typical CCD can be as high as 80 e/pixel. A more typical readout noise for state-of-the-art CCD's is 5–10 (e/pixel)/read. Such a chip is thus a poor detector, unless the photon noise (root N) that is due to signal plus sky background exceeds this. Usually this is possible in less than 10-min exposure with wide-band imaging, but often not with high-dispersion spectroscopy. Because of the much lower sky background in spectroscopic applications in astronomy, CCD's with less than about 10-e noise are required. Tektronix[19] is now making high-quality CCD's with low noise, which are a good match to either imaging or spectroscopic needs.

CCD's exhibit both additive and multiplicative systematics. Thus the order of image-processing operations designed to remove these fixed systematics is important. The following seven steps, discussed in detail by Seitzer et al.,[20] are necessary to remove the basic instrumental signature from the raw data, leaving them in a processed state ready for image analysis (pattern recognition, object classification, photometry, etc.):

(1) *Subtract Bias and Bias Structure.* The dc bias level on the frame, obtained from an overscan region average, is subtracted from each data frame, including calibration and flat-field data. For work with a precision of 10 e or better, a bias structure image, obtained earlier by averaging many bias reads, is subtracted.

(2) *Subtract Dark.* Most CCD's exhibit some low-level LED activity, leading to light pollution during long exposures. A median of many such long exposures, obtained as recently as possible, is subtracted from the object frames.

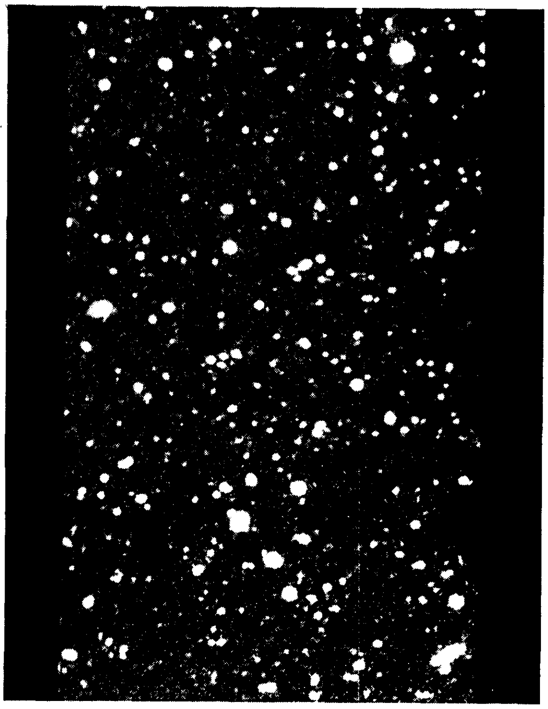
(3) *Divide by Flat Field.* Many short exposures on a diffusely illuminated screen are averaged, for each filter–spectrograph setting. The flat-field exposure level and illumination color must be similar to the data (real-sky) exposures. For spectroscopic applications, the color of the flat-field illumination is much less important. The bias-corrected flat-field master averages are then divided into the object frames, to correct for QE variations (including out-of-focus dust) from pixel to pixel.

(4) *Subtract Fringe Frame (Adaptive Modal Filter).* Narrow night-sky emission lines cause interference fringes on some back-illuminated CCD's bonded to glass, in sky-limited exposures. Either a library fringe frame or the output of an adaptive modal filter (discussed below) is scaled and subtracted from the object frames. Backside-illuminated CCD's that are mechanically supported on their front side (such as Tektronix) have much reduced or negligible fringing.

(5) *Interpolate over Bad Pixels.* A bad-pixel map for the particular CCD in use is input to a nearest-neighbor interpolation routine. Alternatively, if our two-dimensional random offset technique is used, low-level bad pixels will filter out of the final image.

(6) *Remove Cosmic Ray Events.* A 1-pixel-high clipping algorithm (useful only if the desired data are at spatial wavelength greater than 2 pixels) or drift-scan or the ran-

(a)



(b)

Fig. 4. (a) A 1 × 2-min of arc portion of one 500-sec red CCD exposure on a 4-m telescope, after flat fielding but before adaptive modal filtering. (b) The median of 15 such frames, after adaptive modal filtering, stretched 10 times. These pictures are windowed at the sky level: black to white is (a) 10% and (b) 1% night-sky brightness. The faintest objects detected correspond to 200 detected (photons/pixel)/7500 sec.

dom offset technique (described below) is used to eliminate radiation events greater than several times the background noise. It is worthwhile to avoid heavy metals near the CCD, such as in the glass in the reimaging optics.

(7) *Registration of Frames and Median Filtering.* If the random offset technique is used, fractional pixel registration of data frames, followed by median filtering and trimming, is used to produce the final cleaned image.

Sufficient bias, dark, and flat-field frames must be taken to ensure negligible noise in the median-processed images. The excellent dynamic range and linearity of the CCD make it possible to calibrate observations of very faint objects accurately by using short exposures on much brighter photoelectric standard stars. In our new chopping technique, data acquisition for the faint-object survey is done by randomly moving the telescope up to 25 sec of arc, between 500-sec exposures. In general, it is necessary to move the image at least several times the size of the largest interesting object. In processing, we then remove the sky fringing by adaptive modal filtering, subtracting the fringe pattern, and shifting back to a common origin with a program capable of shifting to partial pixel accuracy.

The adaptive modal filter computes the absolute difference between the mean and the median of a pixel over all the images and rejects deviant values until this difference falls below a certain value or a maximum number of values have been rejected. A given pixel is then median filtered over all the images. This works only in uncrowded fields or in fields without extended objects where over 70% of the field is blank sky and under photometric conditions. This is the technique used in our faint CCD survey work. Figure 4 shows a 1 × 2 min of arc portion of one 500-sec exposure before adaptive modal filtering and the median of 15 registered 500-sec exposures after filtering. The systematics have been reduced to below 0.03% of the night-sky background, and the S/N is limited purely by photon statistics. Figure 5 shows a 1 × 1 min of arc area near the south galactic pole, imaged with a limit Schmidt photographic telescope [Fig. 5(a)], a 4-m telescope hypersensitized photographic-emulsion exposure at prime focus [Fig. 5(b)], and the CCD exposure at prime focus of the same 4-m telescope [Fig. 5(c)]. The CCD image is photon-statistics limited: In order to image fainter objects, either a larger telescope or longer integration times would have to be used. However, new weather-related systematics would be encountered in longer exposures. The capability of small telescopes can also be pushed to the photon limit with CCD detectors and the adaptive modal filter. Figure 6 shows the same line before and after adaptive modal filtering, in a 300-sec 1-μm band CCD exposure on a 1-m telescope.

DATA REDUCTION

CCD imagers can create massive data bottlenecks, unless the data are processed rapidly. A typical night's imaging or spectroscopy run using a 300 × 500 pixel CCD may amass 50–100 Mb of object, calibration, flat-field, bias, and dark frames. New 2048 × 2048 CCD's produce 8-Mb images, thus yielding up to 1 Gb of data per night. Mosaics of CCD's covering the usable focal plane of existing and planned large telescopes will produce 10–100 Gb per night. Automated image processing can alleviate this problem. The majority of these data are calibration or ancillary data and need not be saved after their use in preprocessing the object exposures. There are two problem areas: (1) image preprocessing (correction for the detector response, and cleaning) and (2) data reduction and analysis.

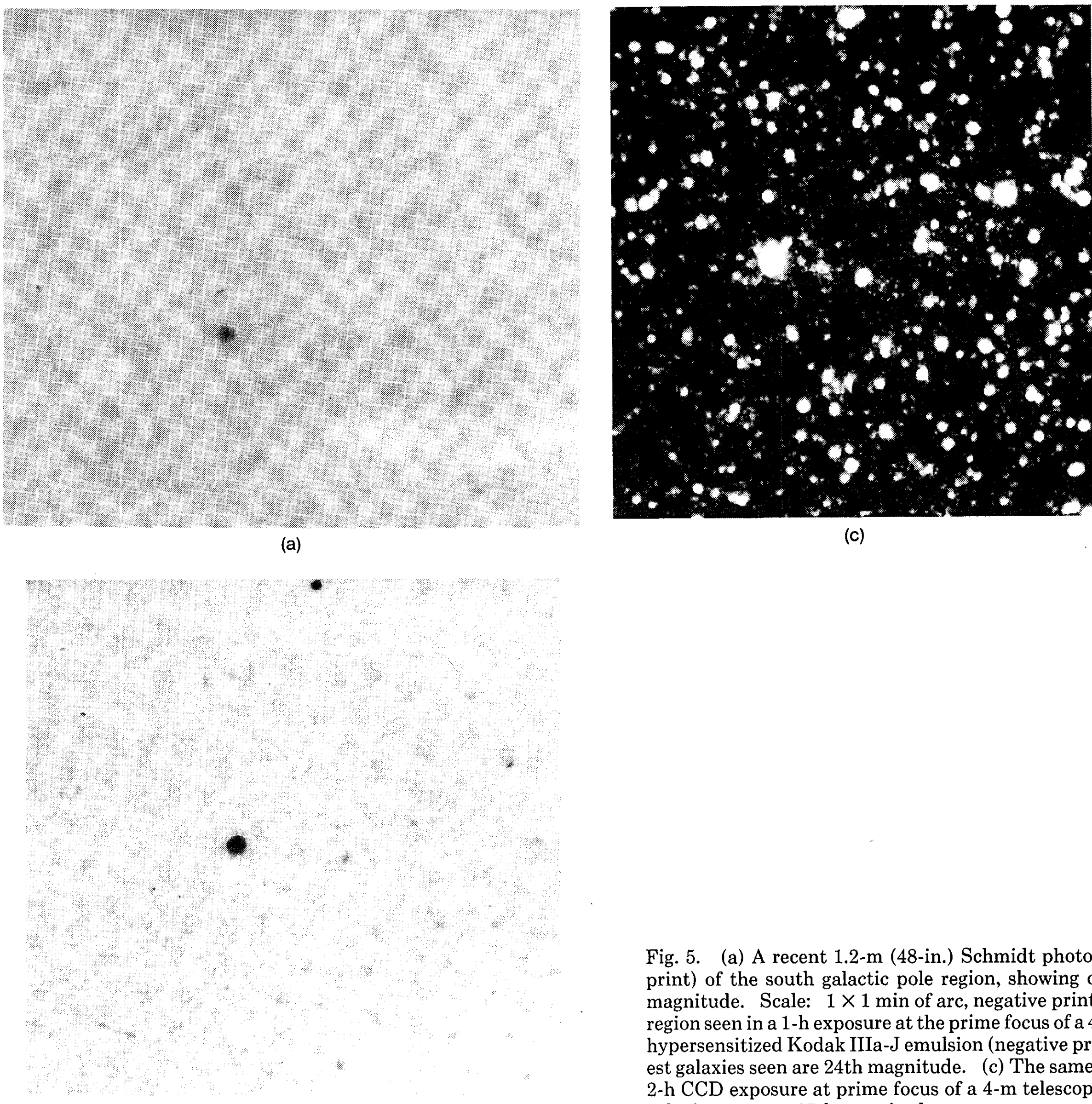


Fig. 5. (a) A recent 1.2-m (48-in.) Schmidt photograph (negative print) of the south galactic pole region, showing one star of 19th magnitude. Scale: 1 × 1 min of arc, negative print. (b) The same region seen in a 1-h exposure at the prime focus of a 4-m telescope on hypersensitized Kodak IIIa-J emulsion (negative print). The faintest galaxies seen are 24th magnitude. (c) The same region seen in a 2-h CCD exposure at prime focus of a 4-m telescope. The faintest galaxies seen are 27th magnitude.

Image Preprocessing and Data Management

The data-management system must have sufficient power to reduce the images taken during one night to final form during the following day. The latter capability is critical to the success of the instrument: The amount of data generated by such a camera is so great that it would quickly overwhelm ordinary computer facilities, and it is imperative that the design of such a system make adequate provision for easy and rapid data analysis. In order to provide the scientist with timely feedback, it would be desirable to have cleaned images within a few hundred seconds of the raw-data acquisition. The comparatively modest amount of cleaned-image data (10–250-Mb/night) that must be archived is well within the capability of high-density tape or optical disk systems.

For example, currently available 68020-based work stations with small array processors are capable of preprocessing these data in nearly real time. The computational rate is quite modest and is easily within the capabilities of small array processors. A more difficult problem arises from the very large amounts of data that must be moved in and out of the array processor. One architecture that can support such operations has the following components: a large, fast data disk (separate from the computer system device); an array processor; a large wide-word buffer memory ported to the data disk, the CCD readout electronics, and the array processor; and a programmable I/O processor controlling data flow from the disk, array processor, and the CCD readout electronics. The I/O processor is very fast: it manages data flow through address control but does not handle data themselves. Instructions for the I/O processor are down-loaded from the control computer.

Automated Data-Reduction Software

Given the large data rates from large CCD detectors, there is a need to perform automated pattern recognition, object classification, and photometry on large image files. The Faint Object Classification and Analysis System (FOCAS) is a software package developed over the past seven years at

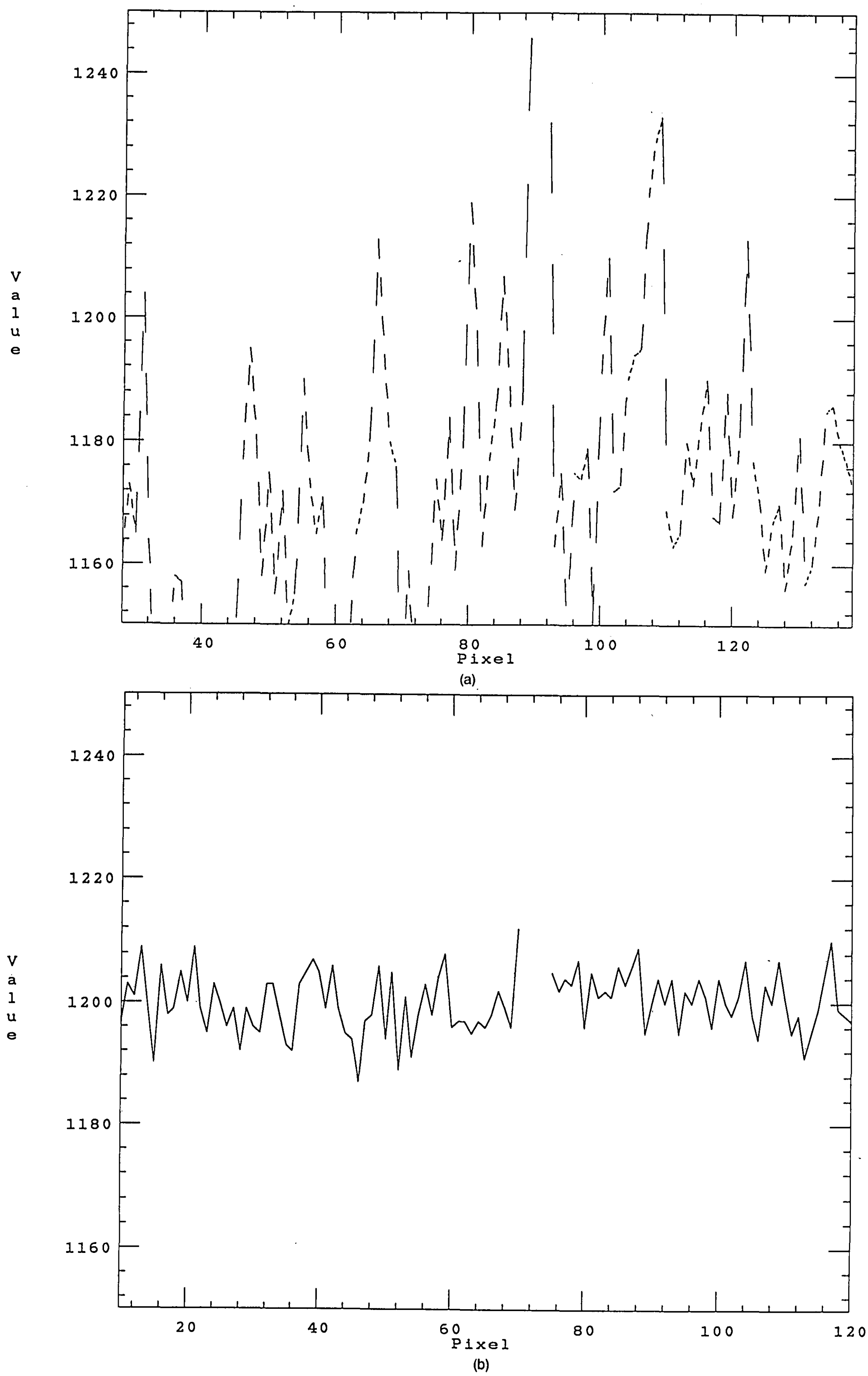


Fig. 6. (a) A plot of the intensity along a line in a 300-sec 1-μm-band CCD exposure on a 1-m telescope. Mostly the positive excursions are shown. The mean value of the sky background was 1170. (b) This same line after adaptive median filtering six such exposures. Some of the remaining intensity peaks are real galaxies. The mean value of the sky background is 1200.

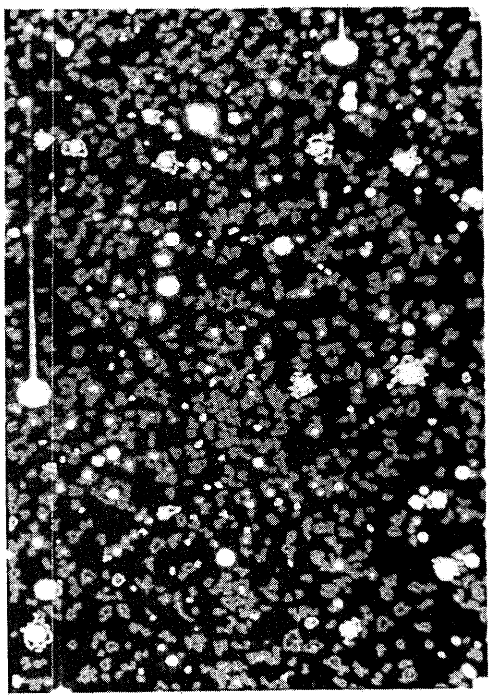


Fig. 7. Color-coded isophotes resulting from a FOCAS run on a CCD image. On the color display, red denotes galaxies, green is stars, and blue is objects with a stellar core but outer nebulosity. A black-and-white photo of the color screen of the output of FOCAS program review is shown here. The isophotes are at 29 magnitude/(sec of arc)^2. Occasional bright stars exceed the full well.

AT&T Bell Laboratories by J. F. Jarvis, J. A. Tyson, and F. Valdes. It is a collection of image analysis and automated pattern-recognition programs and shell scripts written in the C language, designed for automated reduction and morphological classification of astronomical images. Version 1 (v.1) is based on a cluster algorithm that looks for clusters in a multidimensional moment space and was intended for automated classification of 4-m prime-focus photographic plates to 24th-J magnitude.[21] The J band extends from 360 to 520 nm. Photographic noise combined with atmospheric seeing limited the classifier accuracy to $J < 23$ magnitude. A more accurate classifier was developed for studies of stellar counts as a function of color and galactic coordinates.

To extend the range of accurate classification further toward the faint limit, Valdes, Tyson, and Jarvis developed the resolution classifier.[22] It is based on the fundamental theorem in statistical signal recovery in noise: The optimal filter is the time-reserved signal convolved with the noise + signal, divided by the noise power spectral density. In this version 2 of FOCAS the bright unsaturated stars on a plate are averaged to form a mean point-spread function template, which is then convolved with every detected image. Broadened point-spread templates, representing galaxies of various scales, are also convolved with every detected image. A goodness-of-fit algorithm is then used to decide on the final classification of each image and the corresponding probability. Automated splitting of close objects, reclassification, and photometry then occur. This version of FOCAS (v.2) extends the dynamic range from the previous range of 17–23-J magnitude to 17–24-J magnitude for 4-m prime-focus photographic limit plates.

This slower but more accurate version of FOCAS was rewritten by Valdes to incorporate other input data formats as well as new image-handling and data-presentation routines (FOCAS, v.3). Recently, N. Hartsough, T. Kerwin, T. Kovacs, Tyson, and Valdes have included powerful interactive color-graphics display programs that allow the user to identify quickly objects with selected properties, such as color or shape. The FOCAS classifier subroutines have also been optimized, through many runs on simulated and real data, for the CCD data now being obtained. A more efficient algorithm for splitting close objects was developed in 1985.

Catalogs of detected image properties such as various measures of brightness and several central moments are automatically produced. Matched catalogs are produced by automatically position matching detected objects in multispectral and/or multitemporal data. Automatic or user-initiated correlations among these object properties leads to the final reduced scientific output. Searches for new kinds of objects or unusual trends (such as color with position and time-variable objects) can be undertaken with the matched catalogs. These investigations are facilitated by optional interactive color-graphics programs that operate with the catalog and image data. This version of FOCAS is called v.3.2 and is currently running in a Unix environment at Bell Labs. Earlier and updated versions of FOCAS are running at National Optical Astronomy Observatories, Tucson, Arizona, and other observatories. Run time for a v.3.2 on a VAX11/780 without array processor on a 2-h 320 × 512 pixel CCD exposure is currently 39 min. A dedicated work station with fast array processor is a much more effective way of handling the data preprocessing and analysis. Within an hour on a 10 MFLOP computer, the astronomer can have statistical correlation plots for 100,000 objects. An example of recent multispectral research carried out with FOCAS is given in a paper by Tyson *et al.*[23]

Figure 7 shows the result of a FOCAS run on a CCD frame, where objects of a certain color-coded class are surrounded by their lowest-level isophotes. FOCAS has, almost as much as did the high-QE detector, permitted efficient acquisition and processing of survey image data. Commercial hardwired boards are available now that outperform software packages such as FOCAS if a single 1-bit pattern is being searched for. In the spirit of the highly successful AIPS package developed at National Radio Astronomy Observatories, Charlottesville, Virginia, efficient handling and analysis of CCD imaging and spectroscopic data will be enhanced by the introduction of powerful general-purpose software packages such as IRAF, currently being released by National Optical Astronomy Observatories. CCD detectors, combined with small special-purpose computers, are pushing telescopes to their photon quantum limit. Astronomy is currently limited less by CCD and computer technology than by the size of the telescope.

FUTURE TRENDS

IR CCD's, sensitive in the 2–5-μm region, will become available to astronomy soon. A 58 × 62 pixel $InSb_2$ array is already available from Santa Barbara Research Center. The effect of these IR arrays on astronomy will be dramatic. In the area of very large CCD's, the recent fabrication of 20-cm-diameter Si crystals opens the door to future super-large CCD's, if the yield in production can be kept up.

Computing technology shows every sign of being able to keep up with detector development. Detectors of the future may embody photon-imaging detectors as we know them together with analog and digital image preprocessing chips, all on a single very-large-scale integrated chip.

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