Care, Feeding, And Use Of Charge-Coupled Device (CCD) Imagers At Palomar Observatory

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Care, feeding, and use of charge-coupled device (CCD) imagers at Palomar Observatory

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Abstract

Both TI and RCA CCDs have been applied to two-dimensional photometry and spectroscopy at Palomar. The optical, mechanical, and electronic properties of these chips are described along with a discussion of drive, processing, and recording techniques. A focal conversion optical system, the "Prime Focus Universal Extra-galactic Instrument" (PFUEI) is used to more optimally match the Hale 5 meter plate scale. Calibration and data analysis are discussed with illustrations of results.

Introduction

We have been working with CCD imagers at CIT since 1976 when, in support of a proposal to build a CCD based Wide Field/Planetary Camera for Space Telescope, a 400x400 Texas Instruments CCD was made available from the Jet Propulsion Laboratory. Since that time, we have worked with succeeding versions of the TI chips including the 800x800 imagers that will be flown on ST. Most of the work at CIT has been in support of ground based observations, primarily at Palomar. Recently a RCA CCD has been installed by one of us (JEG) in collaboration with J. B. Oke in a Cassegrain spectrograph for use on the 200 inch Hale telescope. Oke will discuss astronomical applications of this device further at this conference.

Physical, electrical and optical characteristics

The basic properties of the various chips we have used are shown in Table 1. All chips are thinned and back illuminated.

Table 1. CCD Characteristics

	TI	TI	TI	TI	RCA
Format	100x160	400x400	500x500	800x800	320x512
Pixel Size	25x25μ	25x25μ	15x15μ	15x15μ	30x30μ
Technology	Alum 3φ	Alum 3φ	Poly 3φ	Poly 3φ	Poly 3φ
Amplifier	surface channel	surface channel	buried channel	buried channel	surface channel
On-Chip Amp Gain	0.5μv/e$^-$	0.5μv/e$^-$	0.45μv/e$^-$	0.45μv/e$^-$	0.3μv/e$^-$
Readout Noise	100e$^-$	100e$^-$	15e$^-$	7.5e$^-$	40e$^-$
Full Well/Pixel	$3x10^5e^-$	$3x10^5e^-$	$3\text{-}7x10^4e^-$	$3\text{-}7x10^4e^-$	$2x10^5$
Operating Temp	-100°c	-100°c	-130°c	-130°c	-120°c

Logic and clock generation

Since all the CCDs we have used are 3-phase devices, an essentially common electronic design has been used which has evolved slowly over the past few years. A block diagram is shown in Figure 1. The clock logic is all CMOS except for the 50Ω line drivers and receivers on the four coaxial cables on which the camera communicates with the data system. The master clock is 2.5 MHz and comes to the camera on one of the control cables. That clock is divided to 1.25 MHz and this 800ns cycle controls all CCD and data functions in the camera. The CCD clock wave forms are generated by a counter-divider chain which feeds a set of RS latches which allows "wire-wrapped" programming. This has proven easier to work than PROM techniques. Timing diagrams for the RCA and TI chips are shown in Figures 2 and 3. The clock generators are housed with the bias regulators, video signal chain, A/D, and parallel-serial converter/line driver circuitry in two "saddlebags" which are clamped to the dewar to provide a high-quality grounded environment crucial to the successful processing of the signals from very low-noise devices.

The logic uses only one external signal in addition to the master clock, a line start command which generates the following sequence: a) the serial clocks (normally always running) are interrupted, b) a vertical transfer sequence is executed, and c) the serial clocks started again. Thus a new line of data is shifted into the serial register with each line start. The line start pulses are asynchronous and are controlled by the remote stand alone data system or computer. The first line start triggers a one-shot which provides a continuous FRAME signal for clock voltage control.

The clock signals are fed, along with the bias and clock voltages, to a driver board inside the dewar. CMOS switches and buffers (4053's and 4050's) are used to drive the clock electrodes on the CCD, with RC networks to control the transition time on their outputs.

Bias voltages

All the bias and clock reference voltages are generated from regulated supply voltages (±18v, +36v) in a card in one of the saddlebags. The serial clock voltages are lowered (though the clocks run continuously) when a frame readout is not under way in order to minimize charge injection (see discussion below). The first line start of a frame switches them but does not cause a vertical transfer; thus the system can settle before the beginning of a read.

Video processing

The video from the on-chip MOSFET source follower is amplified by a low-noise ($2.5\mathrm{nV}/\sqrt{\mathrm{Hz}}$) FET preamplifier designed by J. Janesick of JPL. The amplifier is in the dewar in close proximity to the chip. It is AC coupled with a time constant of about one line time, and contains a clamp to limit the excursion of the large, positive-going precharge feedthrough pulses. This is vital to avoid serious dynamic range limitations in subsequent circuitry. The preamp input noises is equivalent to about $2e^-$ RMS with the output well node capacitance typical of the devices used.

The video now leaves the dewar and goes to a high-impedance DC restoration amplifier which has a low duty-cycle switch (IPC) whose function is to keep the reference level (the video level just before the video signal charge is dumped to the output node) near ground.

The output is again clamped to suppress precharge feedthrough and is fed to a unity gain buffer and a unity gain inverter. These outputs are fed to an integrator through reference (I-) and signal (I+) switches, which form a nearly ideal double correlated sampling amplifier. The reference and signal integration times are, of course, programmable but times near 8μs have been found to be near optimum with the TI output amplifier and to work quite satisfactorily with the RCA amplifier. One wishes to work at a sampling frequency low enough (more precisely, reference to sample time long enough) that 1/f noise dominates but at high enough frequencies so that the inevitable $1/f^2$ noise from various leakage paths is negligible. All of this must be compromised if the resulting read time is intolerably long, a condition already reached with the 800x800 devices. The pixel time is now 25.6μs, which results in a read time near 30 seconds with various overhead contributions.

The integrator output is held briefly after the sample time and goes to a high-speed sample-and-hold on the Intech A-856 16 bit A/D converter board. The conversion proceeds while other functions are performed; the resulting noise has never been a problem. The parallel A/D output goes to a broadside-load shift-register and is clocked out down a serial data coax at 1.2MHz with the accompanying clock pulses sent down a separate cable. Line drivers and receivers are used on the four communication cables so that the system can be used with the ∿400 ft. coax facility cables at the Hale telescope.

The system has proven extremely reliable in operation with only one failure (a voltage regulator) in the three operating systems in about 8 system years of operation.

Control and data recording

The executive control and digital recording are accomplished by use of either dedicated hard wired systems or the PDP-11 series computers at Palomar and Pasadena. These systems generate 1600 bpi 9 track IBM compatible magnetic tapes which are then processed by various available computers including a VAX 11/780 which is dedicated to CCD picture processing in anticipation of WF/PC Space Telescope data.

Instrument signature removal

The CCDs we have used all have spatially non-uniform response which is a function of wavelength. It is also necessary to purposely bias the video signal slightly positive so that the readout noise never drives the A/D input negative. Thus each picture has an "instrument signature" impressed on the data set which must be removed before quantitative analysis can begin. In most cases, a number of unexposed "erase" frames are taken interspersed with normal exposures and then averaged to reduce the random readout noise while preserving any spatially coherent noise and the pixel by pixel bias levels. This "erase frame" data set is then subtracted from each exposed frame.

Another technique has also proved to be convenient for the TI devices and necessary for the RCA chip because of the temperal instability of the serial charge injection. The erase frame is usually only a function of serial pixel location (column number), and therefore can be generated by overscanning the chip by a few rows and using the lines "off the top" of the array. In this way an average erase frame can be generated efficiently for each data frame.

The pixel by pixel sensitivity variations are removed by ratioing each data set, with "flat fields" of the appropriate color. Since, to first order, the detectors are linear only a simple arithmetic division and rescaling, pixel by pixel, is required. To detect the very weakest signals, particularly of extended images, it is necessary to correct for the residual non-linearity by more complex means. Baum, et al. in this Proceedings describe various techniques.

We have found that a diffusely illuminated spot on the inside of the shutter of the telescope dome, viewed by the CCD in its normal observing configuration is the best means of obtaining flat fields. We find it absolutely essential to take flat fields through the telescope with exactly the same optical configuration as used for the normal exposures. This flat fielding technique sometimes fails, occasionally in spectacular fashion, when exposures longward of 7000 Å are required on nights when the line emission from the atmospheric airglow is intense. This is due to a Fabry-Perot effect in the thin CCD membrane which generates "fringes" related to the wavelength of the discrete emission lines when viewing the sky but which are absent in the tungsten illuminated flat field. Other than a careful choice of observing conditions and avoidance of very wide near-IR filters, we have found no solution to this problem. Some CCDs have this problem much more severely than others for no obvious reason. "Fringing" is also seen in spectrographic use of thinned CCDs but is usually adequately corrected by normal flat fielding techniques if the spectrograph is sufficiently stable mechanically. The fringe amplitude is typically of order 10%.

Results

We have tested our systems extensively both in the laboratory and at the telescope and find that neither the one nor the other can be dispensed with if one really wishes to understand the sensors. The gross features of the devices emerge naturally from laboratory test but more subtle (and usually unexpected) properties come to light only when real astronomical data are subjected to scrutiny with some real scientific end. Some scientific results from the TI sensors are to be found in references 1-9; Oke will discuss some recent results obtained with the RCA chip.

Comment

A wise sage has commented (in another context), "One of the more serious disadvantages of this photometer is that it nearly always gives an answer."

CCD performance

The CCD is a nearly perfect device, with problems that appear only because the device performance is so high compared to other detectors that they can be seen easily when the device is pushed very hard. Some anticipated problems, such as non-theoretical dark count behavior at very low temperatures, have not materialized. The three most difficult problems (namely, low-light level transfer inefficiency, spurious charge injection, and flatfield instability) were not expected.

The TI chips exhibit all these properties, but the transfer problem is only evident because of the very much lower readout noise (7.5e^- compared to 40) than that displayed by the RCA device. The problem is evidently in the transfer gate region, a geometrically large and complex interface between the parallel and serial registers. With carefully optimized clock voltages, the trouble appears only with signals smaller than about 100e^- and is almost absent in some devices. It is not clear whether the problem is related to bulk traps in the silicon or irregularities in the potential profiles, but the sensitivity to the electrode voltages suggest the latter.

If the serial clocks are run at a high enough level so that they transfer charge efficiently, they generate charge slowly through some ill-understood avalanche or (more likely) electroluminescent mechanism. This charge injection is a problem if the serial clocks are run during very long exposures. To prevent this phenomenon the serial clock voltages are reduced when the readout is not in progress. There is no real evidence that they should be run at all during exposures, but we do it as a safety precaution against charge moving into the array from the input circuitry, the amplifier, and the (not negligible) dark current in the serial register itself.

The flat fields of the TI chips are unstable at a level of a few tenths of a percent on a timescale of hours; the charges are correlated spatially with the thinning patterns seen in the fields themselves and are almost certainly the result of complex surface chemistry on the (unpassivated) etched back surface. This hypothesis is substantiated by the fact that the effects are much greater in the green than in the red or infrared spectral regions. If it were possible to keep the chip cold and under vacuum all the time, this problem would almost certainly disappear; but we use dewars which are of necessity rather "dirty" with active molecular sieve gettering. And they must be pumped once a week or so which necessitates bringing them to room temperature.

The RCA device at its present stage of development has serious problems as an astronomical sensor, though the problems are almost certainly soluble, and efforts are underway to solve them. The most apparent is the readout noise, which is comparable to that from the early TI sensors, which had similar output amplifiers (surface channel $\sim 50\text{nv}/\sqrt{\text{H}_z}$ spot noise at 100kH_z). The problems in the serial register in our device, however, are so serious that a significantly better amplifier would not really help. Low-level transfer problems in the serial register set in at about $1000e^-$ signal levels; the problem is helped by increasing the serial drive voltages; but before much improvement is observed, the serial charge injection becomes so serious that shot noise and large-scale instability dominate the output noise. The transfer efficiency is aided by slowing the serial clock fall times but with the best parameters for all these, the device is still only marginally viable in its application as a spectrographic sensor. It would, however, perform outstandingly well as a direct imager with the higher signal levels from the sky background attendant to that application.

The linearity of both devices is excellent, typically better than 0.1%. At light levels low enough that the transfer inefficiency occurs, an effective nonlinearity develops because of response irregularity (flat-field) smearing and in the case of stellar photometry, image smearing.

"PFUEI"

The 15 micron pixels of the TI chips are too small for optimum spatial sampling of the 200 inch images even at the prime focus. We have, therefore, built a focal reducer which can also be arranged to be a very efficient low dispersion spectrograph. This "Prime Focus Universal Extragalactic Instrument" converts the f/3.52 image from the 200 inch prime focus Wynne corrector to an f/1.4 image making the effective plate scale 0.40 arsec/pixel, giving a 5-arcminute field with the 800x800 CCD. The instrument is illustrated schematically in Figure 4.

The optics are all readily available commercial items. The collimator is a 135mm focal length f/2.0 Xero-Nikkor photolithographic lens and the camera a broadband-coated 58mm f/1.2 Noct-Nikkor photographic objective. The system is used in conjunction with a Wynne coma corrector, and there are a total of 22 glass-air surfaces and one aluminum reflection in the optical path. The measured system (telescope plus corrector plus PFUEI plus CCD) quantum efficiency is shown in Figure 5 along with the quantum efficiency of typical TI chips. The instrument is an order of magnitude more efficient than the best photoelectric instruments, and one can clearly do better with a less optically complex system. A Cassegrain camera/spectrograph now under construction by Gunn and Oke should have the system efficiency near 40% over a very wide wavelength band.

PFUEI becomes a spectrograph with the insertion of a slit into the primary focal plane and a transmission grating into the filter position. The camera head is then tilted to center the desired wavelength region on the detector. The conversion takes about two minutes and allows straightforward spectroscopy of very faint objects. A finding picture is first taken, the telescope is moved to center the target object, a verification picture is taken, the slit is inserted and a short exposure taken to verify its position. These last steps are done with the guide head locked on a suitable guide star, which will be used for the spectral exposure as well. The instrument is then converted to a spectrograph, and the spectrogram exposed. Flat-field and calibration exposures are taken while the spectrograph is still set up.

The instrument reaches $m_R=25$ in about an hour under moderately good ($\sim$1") seeing and to $m_R=26$ in a couple of hours under very good ($\sim$0.7") conditions. Low-resolution ($\sim$20A) spectra have been obtained for galaxies as faint as $m_R=23.0$ (Z=0.92) in two-hour exposures. Figures 6, 7, 8, and 9 illustrate the performance of the instrument as an imager and spectrograph.

Acknowledgments

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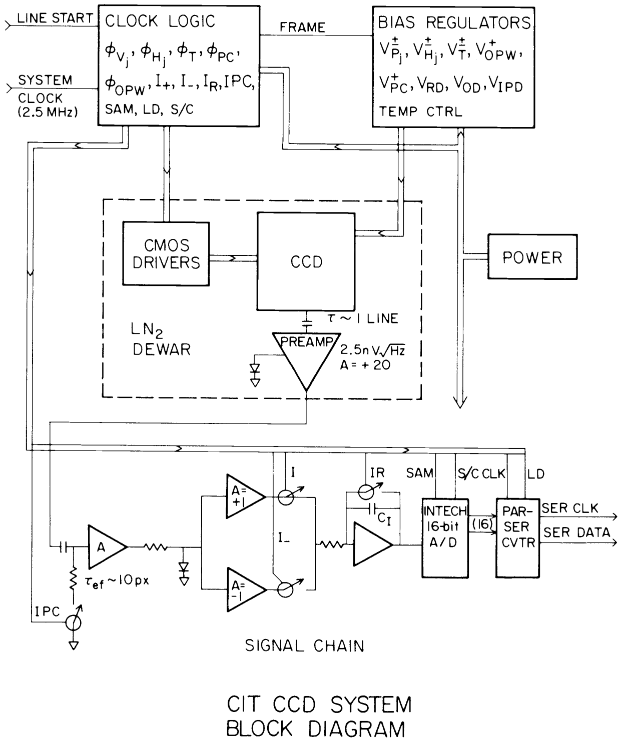

Figure 1. CCD system block diagram.

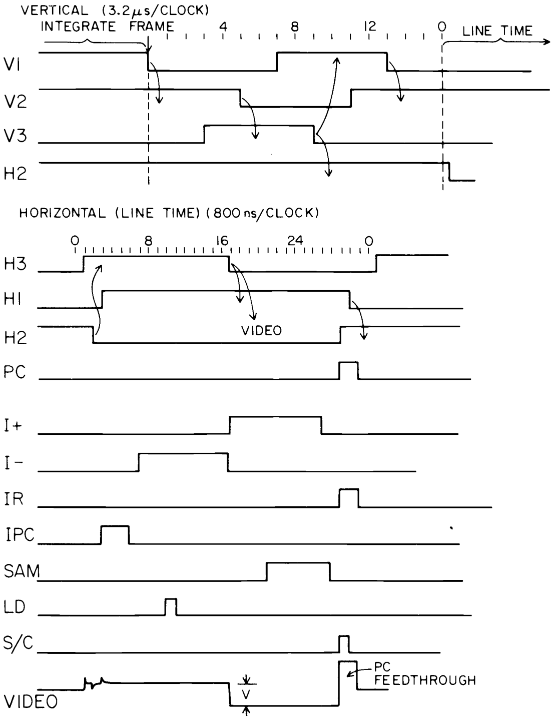

Figure 2. RCA clock timing.

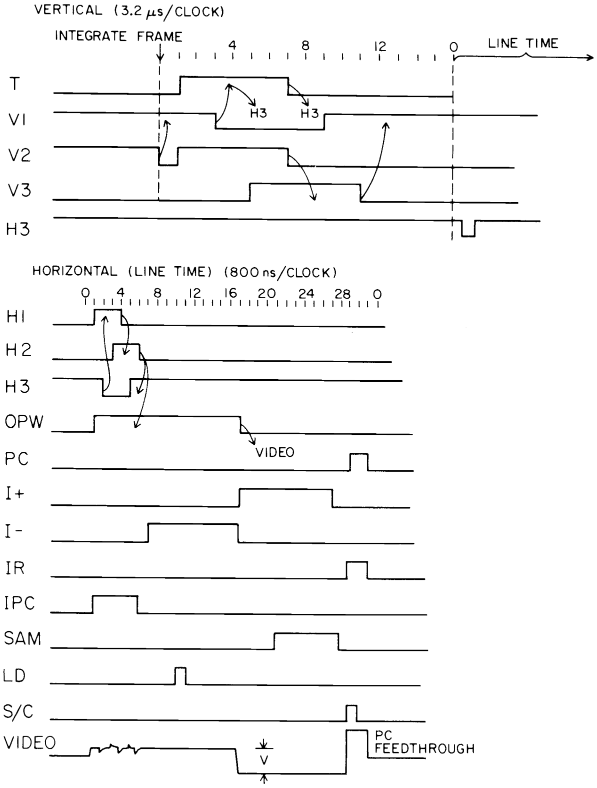

Figure 3. TI clock timing.

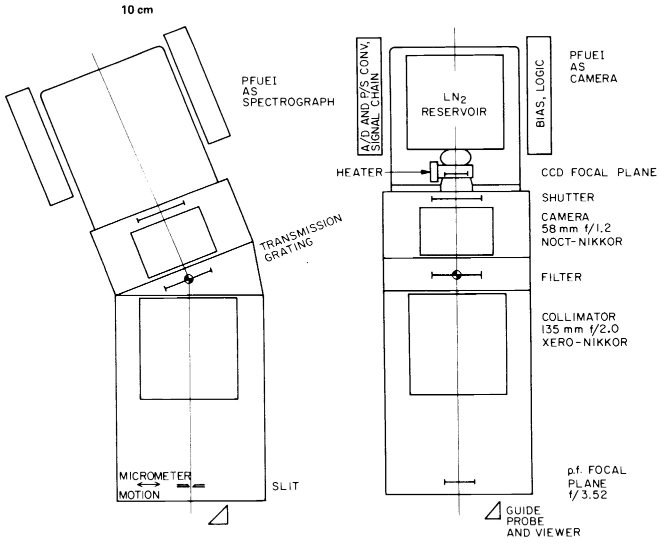

Figure 4. Layout of PFUEI.

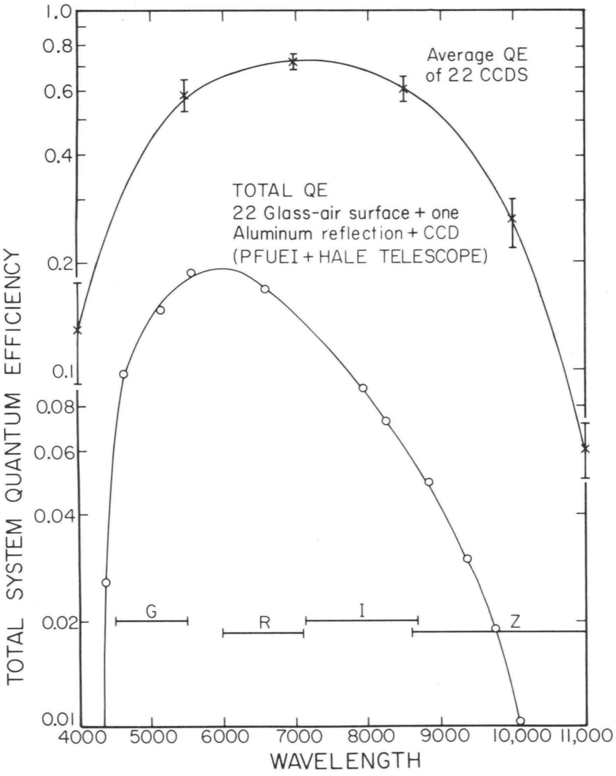

Figure 5. Average quantum efficiencies of TI CCDs and of the total PFUEI/200 inch telescope system.

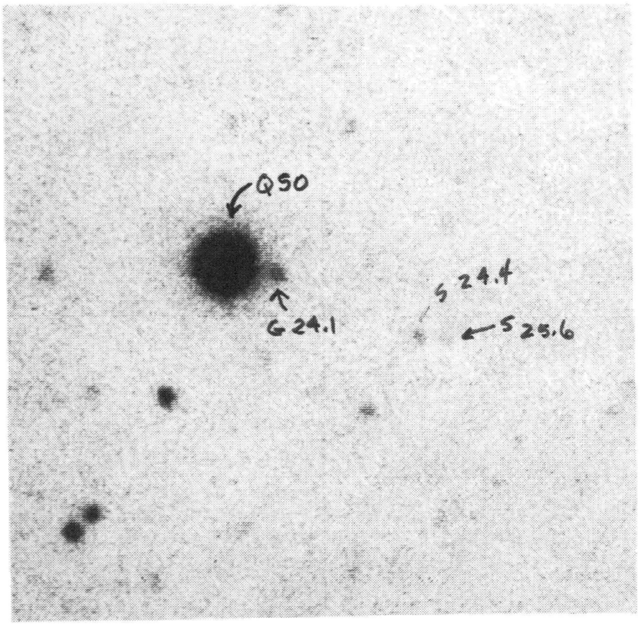

Figure 6. 90 minute 200-inch exposure of QSO 2230 + 114 (Z = 1.037). Galaxy and star images are marked with R magnitudes. Direct 400x400 CCD image.

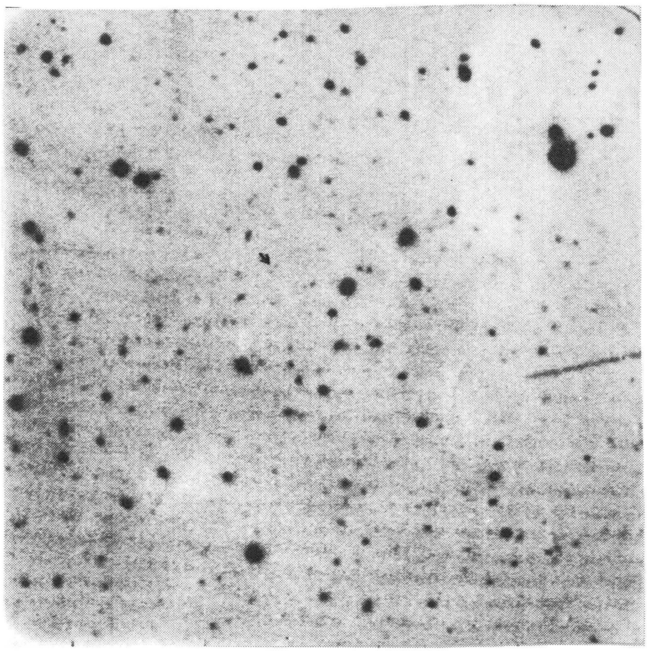

Figure 7. Sum of six 10 minute R exposures with a 500x500 CCD and PFUEI. The marked stellar image is 25.5 magnitude. The trailed image is a faint asteroid. The field is 200x200 arcseconds.

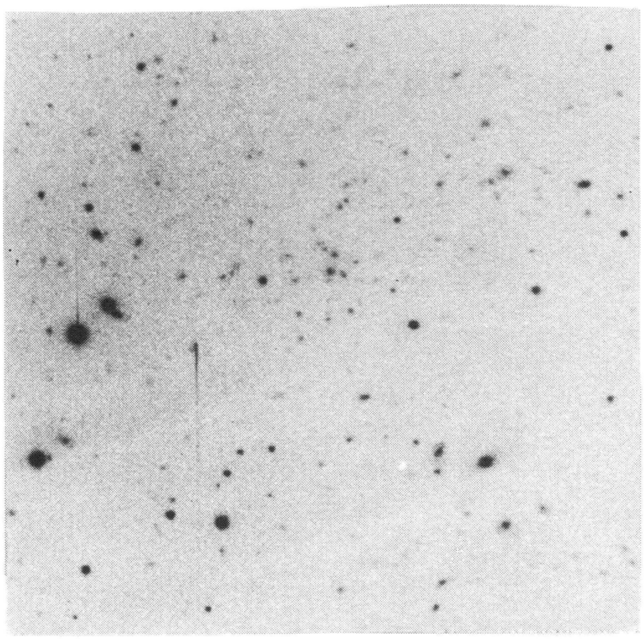

Figure 8. A 5 minute 500x500 exposure of the field of Cl 13kPα, a distant cluster of galaxies of red shift 0.756 (see Figure 9). The field is 200 arcseconds square.

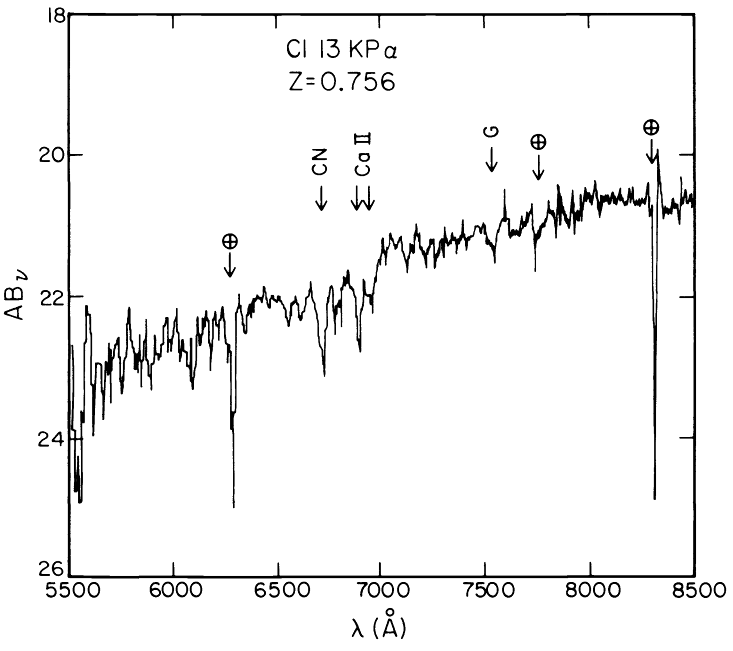

Figure 9. The spectrum of the brightest galaxy in the cluster shown in Figure 8. The exposure time was 100 minutes with the Hale telescope.