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CCD Image data acquisition system for optical astronomy

P N Bhat[1], A K Kembhavi[2], K Patnaik[1], A R Patnaik[3] & T P Prabhu[4]

[1]Tata Institute of Fundamental Research, Homi Bhabha Road, Bombay 400 005

[2]Inter University Centre for Astronomy and Astrophysics, Poona University Campus, Ganeshkhind, Pune 411 007

[3]Nuffield Radio Astronomy Laboratories, Jodrell Bank, UK

[4]Indian Institute of Astrophysics, Sarjapur Road, Bangalore 560 034

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A complete image processing system based on a charge coupled device (CCD) has been developed at TIFR, Bombay, for use in the optical astronomy programme of the institute. The system consists of a P-8600/B GEC CCD chip, a CCD controller, a VAX 11/725 mini-computer to carry out the image acquisition and display on a VS-11 monitor. All the necessary software and part of the hardware were developed locally, integrated together and installed at the Vainu Bappu Observatory at Kavalur. CCD as an imaging device and its advantages over the conventional photographic plate is briefly reviewed. The acquisition system is described in detail. The preliminary results are presented and the future research programme is outlined.

1 Introduction

Optical emission is common to most astronomical objects and optical identification is a prerequisite for the understanding of the nature of a source discovered in any other wavelength band. Like in any other field, in optical astronomy too there is the ever-present need for improved sensitivity, dynamic range, spatial and spectral resolution. An obvious way to achieve these is to build bigger and better telescopes. This, however, is difficult, expensive and time consuming.

In recent years, the need based research on the improvement of the basic optical detector itself, has led to the development of a solid state device, called the charge coupled device (CCD). This combines the virtues of the photographic plate, with those of the photomultiplier based systems and has a high quantum conversion efficiency, dynamic range, photometric accuracy, geometric stability and very low noise level. It has become so popular especially in optical astronomy—where faint object spectrophotometric studies are involved—that it has practically replaced the conventional photographic plate. Almost all the well-known optical observatories in the world have at least one CCD based detector system. In India, we proposed in 1985 to acquire and use such a device in optical astronomy. There is a great need within the country to develop the necessary hardware and software techniques of using a CCD based detector system in optical astronomy.

This paper describes the CCD image acquisition system developed by us at TIFR and installed at the Vainu Bappu Observatory, Kavalur.

1.1 What is a CCD?

A CCD is basically an array of charge storage capacitors, capable of storing the electrons generated by the absorption of photons. The structure of a front-illuminated CCD is shown in Fig. 1. This shows two pixels in a single column of CCD array. Optical photons pass through the electrode array (polycrystalline silicon) and are absorbed in the underlying silicon substrate, generating e^+-e^- pairs. The electrons then diffuse back towards the nearest positive electrode, while the holes diffuse down into the substrate which is held at earth potential. The positive potential can be considered as a potential well in which the electrons are stored. This 2-dimensional array of pixels stores electrons whose number is proportional to the number of incident

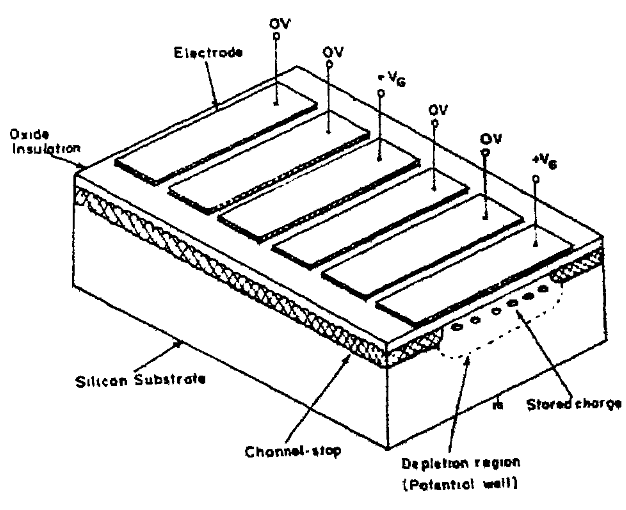

Fig. 1—Basic structure of a charge coupled device (CCD)

photons, which is nothing but the original image. In order to read out the accumulated charge replica of the image, after an exposure, each set of three electrodes is fed with three separate drive pulse trains – raising the potential in an adjacent electrode down the column, then lowering the original electrode potential – affecting a transfer of the charge. This is described pictorially in Fig. 2. In other words a CCD records a 2-dimensional photoelectron distribution which is proportional to the incident photon distribution and this photoelectron distribution can be read out serially enabling one to reconstruct the original image[1].

1.2 How does a CCD compare with a photographic plate?

A typical CCD contains $\sim 500 \times 500 = 2.5 \times 10^5$ pixels. The information capacity of a typical photographic plate (of size say 50 cm × 50 cm) is much larger. It contains the equivalent of $\sim 25000 \times 25000 = 6.25 \times 10^8$ pixels, in the form of fine grains of irregular size of typical dimension 10-20 μm. But to be useful the grain density in a photographic plate must be converted to digital numbers using a complicated and time consuming procedure employing measuring machines (like a PDS machine). In practice, this is done for a small portion of the picture. The image acquired by a CCD on the other hand is available directly in the digital form, though the resolution is limited to about 15-22 μm, this being the typical size of a pixel. Unlike the photographic plate a CCD has a very wide dynamic range (up to 10^4) over which the digital output signal is directly proportional to the incident light. The plate has threshold and saturation effects and generally highly nonlinear response which means that it must be carefully calibrated[2]. Even then there is the problem that the sensitivity may vary across the plate which is very difficult to compensate for[3]. These problems can be solved rather easily in the case of a CCD by the flat-fielding technique.

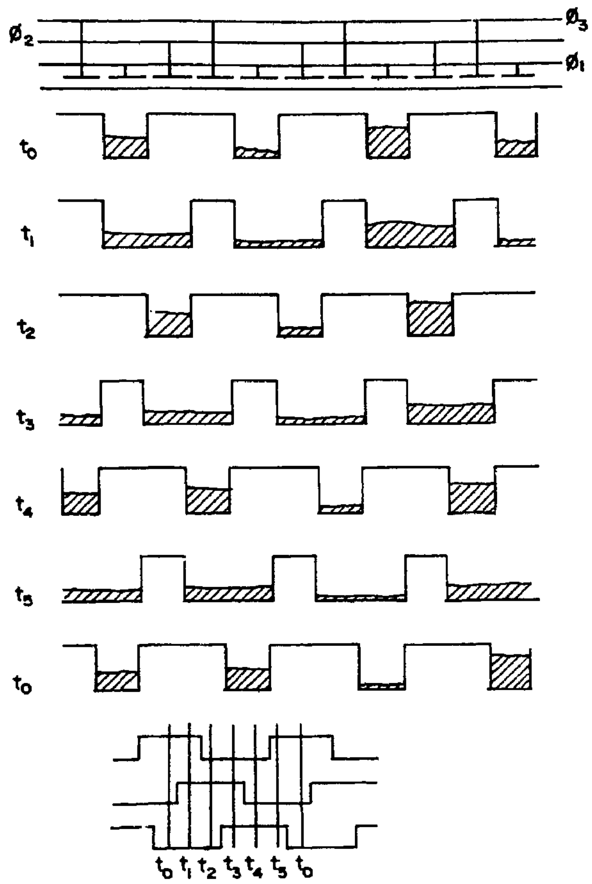

Fig. 2—Time sequence of potentials applied to the electrodes of a 3-phase CCD effecting a transfer of charge to the adjacent pixel

The advantages of a CCD compared to a conventional photographic plate are:

(*a*) *Quantum Efficiency*—A very important parameter in imaging is the photon conversion efficiency. This is defined as the ratio of the number of photoelectrons to the total number of incident photons of a given wavelength. In the case of a photographic plate the quantum efficiency is not easy to define; however, the average value is ≈ 1-3%. This may reduce to as low as 0.05% at low light levels. A back illuminated CCD could have a peak quantum efficiency of 85%: see Fig. 3 for typical wavelength response functions of various optical devices. It is clear that a CCD is the best imaging device available today[4]. Even the best electronic imaging device based on the principle of television, available today, viz. image photon counting system (IPCS) has a maximum quantum efficiency of about 15%.

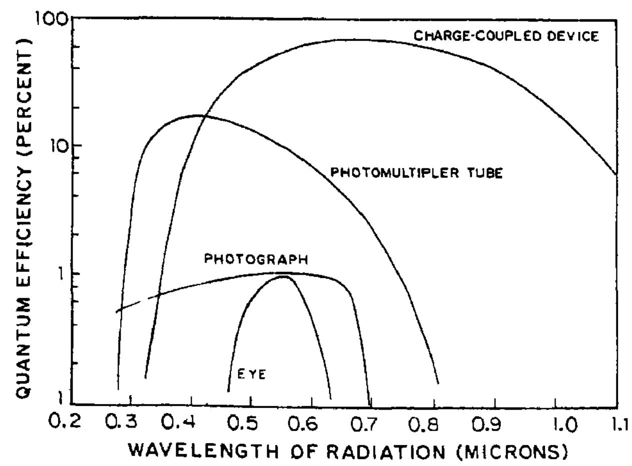

Fig. 3—Spectral response of various optical devices used in astronomy compared to that of the human eye (The CCD imager is superior at all wavelengths except those in the ultra-violet region of the electromagnetic spectrum. The broken line represents the effect of coating the CCD with coronene, an organic phosphor that converts photons of ultra-violet radiation into light photons)

(*b*) *Noise*—This is a parameter which determines the faintest object one can image. Photons are quantized and hence their arrival in space and time is represented by a distribution function. This contributes to the statistical noise in the number of photoelectrons received by each pixel. Addition of noise to an image introduces granularity, thus obscuring fainter details. In any electronic device thermal noise is the most dominant source of noise. However, in the case of a CCD this noise is kept to a minimum by cooling the device to liquid nitrogen (LN_2) temperature. The only other noise in a CCD is contributed by the on-chip electronics. The signal charge from each pixel dumped across the node capacitor is amplified and measured using the correlated double sampling technique. However, some amount of electronic noise is being added in this process. This is less than 10 photoelectrons per read-out for the TIFR CCD. This is called the read-out noise, which decides the faintest object one can image using this device.

(*c*) *The Dynamic Range*—The dynamic range for a device is defined as the ratio of the maximum to the minimum detectable light intensity. A large dynamic range is needed for measuring faint objects in the presence of bright ones, e.g. if one wants to study the faint outer regions of a quasar or a galaxy with a bright, active nucleus, one needs a device with a large dynamic range. In the case of a CCD this is determined by the full well capacity of a pixel (which is $\sim 10^5$) and the read-out noise, giving a figure of $\sim 10^4$ for dynamic range for our CCD. In the case of a photographic plate this is ~ 100. For IPCS this value is severely limited by the maximum count of ~ 5 pixel^{-1}.

(*d*) *Colour Response*—CCDs have a rather wide band-width of colour response from blue to near infrared. This makes the CCDs ideal imaging devices in the near infrared and this property has some special advantages in optical astronomy.

The quantum conversion efficiency of a CCD reduces to zero at wavelengths ≤ 4000 Å. However, recently this limitation has been partly overcome by coating the CCD surface with a wavelength shifter (an organic compound called 'coronene') which gives an efficiency of $\approx 20\%$ even in the range 2000 Å$\leq \lambda \leq$4000 Å (Ref. 4). UV flooding is another technique used to improve the blue response of a CCD[5].

(*e*) *Geometric Stability*—CCDs have a good geometric stability enabling one to identify the optical counterpart of a source in a crowded field. This is in contrast to the IPCS which depends on electron beam focusing and hence is likely to show geometric distortions.

(*f*) *Photometric Accuracy*—This is another important property of a CCD. It responds in a known and reproducible manner so that a given light input always yields the same output. This is important in the accurate measurement of brightnesses of celestial objects. In addition CCDs have perfectly linear response like the electronic devices.

2 Hardware

2.1 CCD and its controller

From the point of view of developing a CCD based image acquisition system, it was decided to procure the electronics like the CCD controller and develop the necessary software in house. A CCD controller system developed at Cambridge (UK) was acquired. The system contains a GEC P8600/B CCD with a very low read-out noise of ≤ 10 electrons and a spectral response as shown in Fig. 4. The CCD having 576×385 pixels is mounted on a LN_2 dewar so that it can be operated at temperatures in the range 100-180 K to reduce the thermal noise and dark current. The electronic hardware to operate a CCD in such a system has several functions:

(i) to generate appropriate bias voltages and clock signals to drive the CCD properly;

(ii) to process the analogue signal output by the CCD so as to minimize the overall system noise and to digitize the signal accurately;

(iii) to organize all communications with the host computer; and

(iv) to permit easy diagnosis and maintenance of system operations and performance.

2.2 Computer system

Due to a large amount of data ($\approx$ half a megabyte per picture) to be handled while using the above device for imaging purposes, one has to necessarily use a fast digital computer to control the device and to acquire data. From the point of view of compatibil-

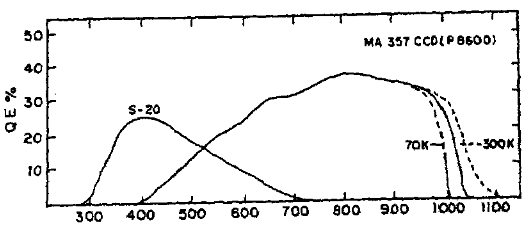

Fig. 4—Wavelength response of a GEC P8600 CCD compared to that of a phototube. The change in the long wavelength response for two operating temperatures is also shown. The solid line corresponds to the response at the normal operating temperature of 140K

ity and service, a VAX (UNIBUS based) system with its own tape drive for data storage and transport, and a image monitor for data display was acquired. The system consists of:

(a) a VAX 11/730 CPU, 1 MB RAM, a RC25 compact disc storage system with a storage capacity of 52 MB (of which 26 MB is removable while the rest is fixed) and a TU58 cartridge for booting and system diagnostics;

(b) a DR-11 K parallel 16 bit interface card for data i/o from/to the CCD controller interface;

(c) a VS-11 raster-scan image display monitor (16 colours);

(d) a VT-220 VDU used as a console;

(e) a LA-50 dot matrix printer; and

(f) a TU-80 streamer tape drive for data storage and transport.

3 Software Development

The complete software package required for testing and operating the CCD, data retrieval, storage, image display, image transport and preliminary analyses were developed by us. The basic software required to acquire the image and store was written in the VAX/VMS MACRO in order to cut down the operating system overheads. For example, FORTRAN-callable assembly language routines for getting the image from the CCD camera and re-scaling the image were too slow. Hence they had to be written in MACRO. This is mainly because Fortran routines make use of the system "QIO" service calls, of the VAX/VMS operating system which are not fast enough for the large number of data i/o operations.

3.1 MACRO routine

The Macro routine encapsulated the input/output operations and the mandatory delays necessary for the optimum functioning of the CCD controller. For example after requesting a parallel transfer a settling time of ~ 120 μs had to be allowed for; similarly a serial transfer needs ~ 70 μs to complete. The ADC needs 10 μs for 16 bit conversion of data. In addition one has to allow for the propagation time to and from the controller to the computer interface. These delays have to be allowed for after respective operations in order to achieve best possible charge transfer efficiency. The image acquiring Macro routine also had the built-in provision of hardware, on-chip summing of charges from a required (a maximum of 16) number of rows and/or columns. This facility is particularly useful for a quick read-out of an image at the cost of resolution. It is also a useful feature for a fast acquisition of a pre-determined window on the image while the rest of the image is summed, acquired and rejected. It also has the provision of acquiring a specified window of the image. This feature is also useful for the initial focusing of the star image on to CCD. This program takes these inputs in the form of parameters and executes the following sequence of routines:

(i) On entry it accesses the device registers by mapping the physical page containing the i/o addresses into a dynamically allocated virtual memory page.

(ii) Before transfer it clears the transfer gate registers of the CCD by reading and rejecting the data once.

(iii) It resets the camera controller. This transfers the multiplexer control to the double correlated sampling (DCS) module.

(iv) It reads the specified window or full image. It sums the required number of rows and columns as mentioned in the input parameter list and fetches the digital pixel data.

(v) On exit it deletes the virtual page mapping device registers from program space.

This routine provides a much faster way of reading in the image than via "QIO" system service calls of VMS.

3.2 FORTRAN programs

The image display software package consists of a series of FORTRAN 77 programs and subroutine libraries. Various features of the VAX/VMS operating system have been used to make the use of the programs simple. As a result, an observer who is not familiar with the details can simply use the programs by typing in just a few simple instructions at the console to obtain the required exposures, to store and display them and also to monitor the system performance. No knowledge of the details of the software package is required for this purpose. The programs are menu driven and user friendly.

The main programs in the software package are the following:

(*a*) *CCDTEST*—This program is invoked at the very beginning of an observing session. This package makes use of the system "QIO" calls of the VMS and the software driver for DR-11K i/o operations available in the operating system. The program checks all the commands as well as data. The main function of this package is to ensure the proper functioning of the CCD controller and the communication channel between it and the computer interface. The controller can operate in the 'ECHO' mode when it echoes all the commands sent from the host computer. With the controller in this mode program compares all the information sent with that received and informs the user of any discrepancy at any stage. Proper reception of the instructions to the controller can also be ensured by examining the LED display on the controller.

(*b*) *MONITOR*—In the CCD controller various potentials to the CCD drivers are critically tuned to ensure best performance. This includes various power supplies, clock and bias levels, time constants, amplifier gains, etc. Invoking this program initiates the reading out of these DC levels on different modules of the controller, as well as the temperatures at various points on the dewar. It is necessary to do this periodically during an observational session to ensure the integrity of the system, to ensure the constancy of the various system parameters and also to monitor the temperatures. The results obtained are printed with the date and time for a permanent record.

(*c*) *CCDRUN*—This program is used to obtain an exposure and acquire the image data from the CCD. When it is invoked, various prompts are requested, and the responses are maintained as a header which identifies the data file and provides information about the object observed. The information includes the source name, source coordinates, filter used, exposure time, date and time of observation, data file name, etc. The program also allows the required number of CCD flushing operations to be performed – this is necessary to prepare a CCD for an exposure—and then carries out an exposure for a requested duration and then stores the resultant data in binary form in a file with a chosen name.

(*d*) *DISPLAY*—This program uses the image file to create a new file in a form suitable for use by the VS-11 display system. It then displays the image on the colour monitor. This program has the provision to use the user defined dynamic range as the display uses only 4 bits while the data has 15 bits. This program also has the facility to pan the image up and down, and zoom a selected window of the image, so that various features of the image could be examined. Once an image is displayed, it is possible for the data from a chosen portion of the image to be displayed as digital numbers. The chosen portion can either be a 2-dimensional region, or a single row from the frame. It is also possible to print out a selected length of a row of the image in the form of a histogram. This is useful in estimating the width of a point source image. Numerical display allows the finer features of the 16-bit data, not discernible on the 4-bit colour display, to be examined. This enables the image size and shape to be estimated (FWHM of a point source for example), which helps in fine focusing.

(*e*) *FITS*—For image data transport an international standard is available for writing the data on to a magnetic tape[6]. It is called flexible image transport system (FITS). Many professional image processing packages like IRAF, SDAS, AIPS, etc., accept data in the FITS format directly which makes it very convenient for processing the acquired images. This Fortran package translates the image data in the binary form into FITS format and writes on a magnetic tape.

Each of the above programs, and several other minor ones, can be invoked by simply typing in the name of the program at the console. The prompts requested by the program are self-explanatory and the actions taken by it are displayed from time to time.

Acquisition of single frame from the CCD requires about 80 seconds, apart from the time spend in the exposure and in flushing. Every flushing operation requires about 6 seconds. The DISPLAY program requires about 90 seconds to display the acquired image on the image monitor. Much of this time is spent in converting the 16-bit data to a 4-bit form required by the VS-11 display system.

4 Final System Integration and Testing

As the saying goes the proof of the pudding is in the eating! One has to integrate the whole CCD system to ensure a proper functioning. Using our own hardware and software system we had to ensure that the image is properly acquired and displayed on the monitor. For this purpose a camera was designed in order to generate an image of a transparency on a plane such that when the CCD dewar is placed on the camera the focused image would fall on the CCD surface. This camera was so designed as to take any transparency like a photographic slide or a microscope slide and produce an image on the CCD. There is a shutter in front of the lens such that the CCD could be exposed for a required amount of time while a light source, whose intensity could be controlled, was placed below the slide to illuminate. Images of various types were acquired and displayed using this system ensuring that the whole system was performing as per design. The data were written on the magnetic tape, read back into the computer and redisplayed.

Because of the smallest f/d ratio at the prime focus (3.25, for VBT), the angular resolution of the CCD is the lowest, i.e. 0.6 arcsec pixel^{-1}. As a result the CCD covers a field of 5.76 arcmin × 3.85 arcmin in the sky. The night sky brightness at $\lambda = 650$ nm, is 4.5×10^{-18} ergs s^{-1} cm^{-2} st^{-1} Hz^{-1} (Ref. 7) and the red luminosity of typical point source (a star) = $10^{-(0.4(R_0+39.39)}$ W cm^{-2} Å^{-1}, where R_0 is the red magnitude of the source. From these, we calculate the faintest point source one can see at 3 σ level during an hour's observation, using the CCD at the prime focus of the VBT to be, $R_0 \approx 25.8$ (Ref. 8). This is based on the assumption that the seeing is ≈ 1 arcsec and a broad band ($\Delta\lambda = 1000$ Å) R-filter is used. The limiting magnitude for a photographic plate on the other hand is ≈ 19.0 (Ref. 9). For an extended object the limiting magnitude is ≈ 24-25 arcsec^{-2}. This depends on the image size, photon distribution in the image, etc.

5 Image Processing

When a human being receives and uses visual information we refer to the process as sight, perception or understanding. When a computer receives and uses visual information we call it computer image processing and recognition. An important need for image processing is simply to improve the image quality for human viewing[10].

5.1 Software techniques

Software aspects of image processing can be classified into two parts:

(a) pre-processing and (b) post-processing.

(*a*) *Pre-processing*—Some of the important aspects of pre-processing are:

(i) Flat fielding to remove the effects of pixel to pixel sensitivity variations: This is generally done by dividing the frame by a high signal-to-noise exposure of an evenly illuminated field, called the flat field. The flat field has to be generated by imaging a uniformly illuminated surface like the illuminated dome, or the dawn sky or the late evening sky and choose the best among them. We tried all these techniques and found that the dome illumination gives fairly satisfactory flat-field without any systematic spatial gradient in the field. This flat-field was used in the preliminary analyses of the selected area images. Fig. 5 shows one such pre-processed image of NGC 4261. This was taken on the prime focus of the Vainu Bappu Telescope in January 1987 using a broad-band R-filter in a 5-second exposure. Image processing was done at the National Image Processing Centre at the Radio Astronomy Centre, Ootacamund.

(ii) Bias subtraction: or subtraction of a constant number which is a sum of the rms read-out noise and the bias level, if any.

(iii) Dark current subtraction: using a mean or median dark current frame from a large number of similar long dark exposures, scale if necessary: This takes care of the dark current contribution to image during the exposure.

(iv) Cosmetic correction: There are certain defects in any CCD due to the technical difficulties of making it. As a result there will be a few isolated pixels and/or columns which always show high/low counts irrespective of the signal. Also, certain pixels or group of pixels record large counts due to cosmic ray interactions. Cosmic ray rate depends on the size of the device and it is around 6 min^{-1} in our CCD. These defects have to be identified and removed by several software methods.

(*b*) *Post-processing*—Post processing of an image is to subject the image to enhance or highlight certain aspects of the image. For example, applying a low-pass filter enhances slowly varying (across the field-of-view) features of the image, whereas a high-pass filter enhances the image contrast. Similarly, edge enhancement, interpolation techniques to take care of the defects, image restoration, etc., are some of the specialized techniques used in post-processing.

It is not necessary to develop these techniques from the scratch for professional image processing packages are available—like IRAF (image reduction and analysis facility, developed by the National Optical Astronomy Observatories), SDAS (science data analysis software, developed for the analyses of CCD data from Hubble Space Telescope), STARLINK and MIDAS. Two of these packages, IRAF and SDAS were procured free of cost and installed on the VAX 11/780 at TIFR. A SUN/IRAF image processing system also is now available at TIFR, Bombay, and the analysis will be done there in the future.

Fig. 5—Image of an elliptical galaxy NGC 4261 (total apparent photographic magnitude = 11.7) taken using the TIFR CCD on the 2.34 m VBT at Kavalur, using broad-band R-filter (Exposure = 5 s. The vertical lines seen in the image are due to the bad columns in the CCD)

6 Future Programmes

Observations which are planned to be carred out can be classified into three categories:

(a) Direct Imaging
(b) Photometry and
(c) Spectroscopy

6.1 Direct imaging

This involves determining the light distribution across extended objects using different filters. The prime focus of the 2.34 m VBT is ideally suited for this purpose, because of the availability of a good quality image with least loss of light as well as the plate scale which provides a field-of-view which is larger than that available at other foci (see section 6.2). Since the prime focus was the first to be available, our observing programme has initially concentrated on imaging. Following are some of the projects to be carried out using direct imaging technique using a CCD:

6.1.1 *Surface Photometry of Galaxies*—The surface photometry of galaxies is of great value in the investigation of various properties like mass-to-light ratios, the photometric characteristics of bulge and disk components, the relationship between the presence of an active nucleus and the structure of the galaxy, etc. The determination of the correlation between various parameters, e.g. mean surface brightness as a function of Hubble type, can be used to place constraints on various models of galaxy formation and evolution. The distribution of various parameters as a function of galaxy environment can provide valuable insight into the effect of galaxy-galaxy interaction as well as galaxy morphology and other properties[11-14].

6.1.2 *Surface Photometry of Galaxies in an X-ray Cluster*—The X-ray emission from some clusters like 2A0335 + 096 has been recently studied in detail using the EXOSAT and Einstein Observatories. Except for the spectroscopy and narrow-band photometry of the central D-galaxy (on which the X-ray emission is also centred), no optical data are available. We propose to undertake a detailed optical study of the cluster. In the first phase the surface brightness profiles of the galaxies will be studied using broad-band filteres. At the distance of the cluster ($z = 0.035$ for the cD-galaxy in 2A0335 + 096), a typical galaxy of 30 kpc size could have an angular size of ≈ 30 acrsec, which will occupy ≈ 50 pixels in our CCD. The entire cluster could be covered in ≈ 30 exposures of 20 min for each filter. The data on colour distribution among the galaxies of the cluster, as well as colour gradients in the more prominent galaxies would allow the study of the effect of increasing density of the hot inter-cluster gas as one moves towards the centre. Cooling flows in the cluster are likely to drive star formation inside the accreting galaxies, thereby producing strong colour gradients in them. Our proposed optical study would help explore this possibility in detail[15].

These observations will be followed by narrow-band imaging of some of the more prominent galaxies in the cluster, as well as detailed spectroscopic investigations to measure red-shifts, velocity dispersion, luminosity function, etc.

6.1.3 *Morphology of Extended Emission Line Regions Associated with Radio and Other Active Galaxies*—During recent years a close connection has been established between radio jets and optical emission line regions in the galaxies. The combination of detailed optical and high resolution radio studies have shown that interstellar clouds may collide with radio jets causing the jet to bend and the radio emission to flare-up[16,17]. Optically emitting gas regions (of the size of a kpc) have been found in a number of elliptical galaxies.

Associations between radio features and emission line features are planned to be studied using narrow-band filteres at [O III] $\lambda 4959 + \lambda 5007$ or H_α + [N II]. The bands are only ≈ 10 nm wide, and hence only a few hours of observing time is required for each galaxy, including two filters for line and continuum images. A sample of different kinds of galaxies is being prepared and a formal observing proposal is being written.

6.2 Photometry

Because of its high sensitivity, the CCD is ideally suited to performing photometry on faint objects. During the course of calibration, it should be possible to reach similar magnitudes with broad-band filters in a few tens of seconds of exposure. We plan to use the CCD to obtain colours of a large number of stars in open clusters. We will use these to obtain the H-R diagram for these clusters, providing clues to the evolutionary history of the clusters, their age, metallicity, etc. The study of globular clusters is of special importance at the present time, because of important theoretical work on the dynamical evolution of their cores which has been done recently, as well as the realization that their cores are fertile grounds for the production of exotic binary systems and millisecond pulsars.

6.3 Spectroscopy

This requires spectrogrpahs which are more conveniently mounted at the Cassegrain focus of an optical telescope. We plan to initiate a programme of spectroscopy of planetary nebulae, HII regions, Active Galactic Nuclei (AGN) and quasars. Here again the high sensitivity of the CCD will allow 2-dimensional spectroscopy across an extended object to be performed. These studies could be used to complement the narrow-band imaging described earlier.

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