Charge Coupled Devices (CCDs) in X-ray Astronomy

D. H. Lumb, G. D. Berthiaume, D. N. Burrows,
G. P. Garmire and J. A. Nousek

*Department of Astronomy and Astrophysics, 515 Davey Lab.,
Pennsylvania State University, University Park PA 16802, U.S.A.*
(Received 17 September 1991; accepted 23 December 1991)

Abstract

The application of CCDs to X-ray imaging and spectroscopy for astronomy is described. The requirements which differ markedly from those of traditional optical applications are highlighted. Results of recent research programs to optimize CCD X-ray response are presented. It is shown that very high quantum efficiencies and Fano noise limited energy resolutions can be obtained. A number of issues related to the practical implementation offuture instruments are reviewed.

1. Introduction

CCDs are widely employed in ground-based astronomical applications, and are key components of several recently launched space missions. However it is only now that a number of important X-ray astronomical applications of CCDs have reached critical development stages, so that this is an appropriate time to review the application of space-borne CCD instruments to cosmic X-ray astronomy, and highlight the particular concerns which are being addressed for X-ray instruments, as distinct from optical applications.

CCDs were rapidly developed after their invention and were being considered as candidate detectors for the *Large Space Telescope* as early as 1972 [Sequin]. Ground-based astronomers benefitted enormously from the developments funded through this program and from the manufacturers' own in-house programs to develop CCDs as solid state replacements for broadcast standard TV tubes. Fortuitously, some of these devices were able to operate in standard commercial applications and also at the low light levels and cryogenic temperatures required for astronomy.

For over a decade CCDs have been performing useful scientific observations
at ground-based observatories, where their high dynamic range, linearity and sensitivity to low surface brightness features have made them the sensor of choice for a wide range of observations. In space-borne applications, they have been used on the *Giotto* mission to observe Halley's comet [Keller et al], the *Galileo* planetary mission [Belton et al], and of course the Hubble Space Telescope [Westphal et al].

The first sounding rocket payloads for X-ray astronomy which utilized CCDs have recently been launched [Burrows et al]. Meanwhile, a number of major X-ray astronomy missions have been proposed, or are under development, for which CCDs have been chosen as the focal plane detector. In the near term, these will include the Japanese-US *Astro-D* mission, which will be the first cosmic X-ray astronomy satellite to fly CCD detectors. *Astro-D* will be launched in early 1993, and two of its four X-ray telescopes will be equipped with CCD focal planes. The scientific objectives of *Astro-D* require relatively high spectral resolution (E/o'E 10 - 50) over a broad energy range (0.3 - 10 keV), with good throughput at the iron features near 7 keV. The CCD detectors have therefore been optimized to maximize spectral resolution and high-energy quantum efficiency. The angular resolution of this mission will be limited by its conical foil mirrors to about 2 arcmin (half-power diameter).

The *JET-X (Joint European X-ray Telescope)* instrument is expected to be launched in 1994, and will utilize CCDs at the focal plane of two co-aligned telescopes [Wells and Lumb]. *JET-X* will offer higher angular resolution (10 - 20 arcsecs), but with a lower collecting area compared with *Astro-D.* The scientific goals emphasize the source detectability via the improved imaging capability. In the case of *Astro-D*, the high spatial resolution of the CCDs will not be exploited to the full, but their excellent energy resolution will be a key parameter. Conversely, for *JET-X*, the improved angular resolution is obtained at the expense of lower throughput, and the performance features which affect imaging properties have received greater attention in the instrument design.

Somewhat farther in the future, the two world-class observatories, NASA's Advanced X-ray Astrophysics Facility *(AXAF)* and ESA's X-ray Multi-Mirror Mission *(XMM)*, will exhibit a similar complementarily. *AXAF* will have a diverse range of instruments, including imagers exploiting the very high angular resolution properties of the *AXAF* mirrors, whilst the *XMM* observatory has been designed with an emphasis on spectroscopic observations. The AXAF CCD Imaging Spectrometer (ACIS) experiment [Garmire et al] will combine high angular resolution imaging with good energy resolution, and provide a dedicated array of CCDs in the same assembly for readout of transmission grating spectra. *XMM* will deploy 3 EPIC *(European Photon Imaying Camera)* CCD focal plane cameras behind its three mirror systems for moderate angular resolution, non-dispersive spectroscopy [Wells and Lumb]. *XMM* also has reflection grating spectrometers fixed behind 2 mirrors, and these will utilise dedicated CCD instruments as their readout element [Brinkmann et al].

It can be seen that different instruments place different demands on the CCD attributes. We will demonstrate that these requirements may conflict in some cases. Therefore detailed trade-off studies must be made in each case. This work explores some of these issues, and reviews the development status of CCD research for X-ray astronomy applications.

In Section 2 we examine the the mode of operation of CCDs, contrasting the requirements of X-ray and optical applications. Some of the key developments of in the attempts to optimize CCDs for X-ray astronomy are discussed in Section 3, where we also note recent examples of performance data obtained.

2. **CCD Operation**

Figure 1 shows a simplified representation of a *frame transfer* CCD. An array of vertical electrodes is formed over the silicon surface and horizontal charge transfer columns are defined by implanted channel stop regions in the wafer surface. These orthogonally aligned elements are produced by conventional MOS fabrication procedures. Application of suitable bias voltages to the electrodes produces a matrix of potential wells which define the CCD picture elements.

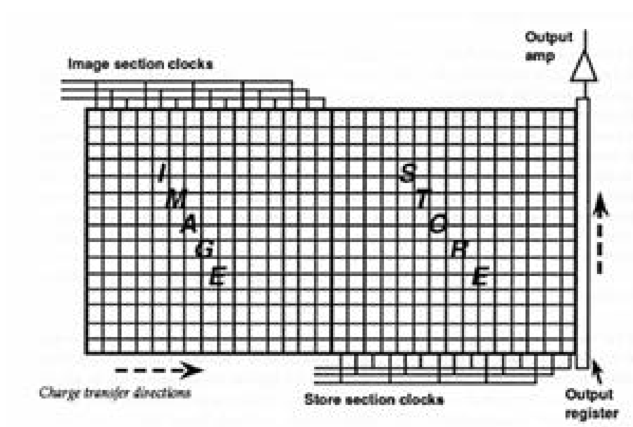

Figure 1. General layout of a frame transfer CCD

The array operates as follows: when an image is focussed onto the CCD photons which penetrate the electrode structure generate electron-hole pairs in the underlying silicon substrate, and the signal charges are stored in the potential wells beneath the electrode structure (gates) After an appropriate image accumulation time, clock pulses are applied to the electrodes to shift the potential wells and their associated charges across the device. Rows of data are moved one-by-one in parallel to the output register with each parallel clock pulse cycle. Each row placed in the output register is then moved pixel-by-pixel to the output node. At the end of each pixel clock cycle, the charge measured at the node is uniquely identified with a pixel address. For incident light in the visible band, the charge magnitude is proportional to the illumination level at the pixel.

The electrodes are generally arranged in two groups, one group is fabricated over the left half of the array, and a second group over the right half. If the entire array is photosensitive, the two groups may be wired in parallel using identical clock signals. When operated in this way as a single array the CCD is said to be in a *full-frame* mode of operation. Alternatively, the right (store) half may be shielded from light, and used to store successive image data frames previously collected in the left (image) section. This mode of operation is generally used for TV imaging and is called the *framestore* mode of operation. This eliminates the requirement for a mechanical shutter to shield the array during readout, since the data transfer from image to store section is accomplished in a fraction of the time (msecs) taken to read out the data in the array.

2.1 Contrasting optical and X-ray applications

A visible light photon releases only one electron-hole pair, and consequently many photons must be collected in each pixel for a measurable signal to be produced. Therefore at visible wavelengths CCDs are used as integrating detectors, and typically the astronomical image exposures are several minutes long. Conversely, a single X-ray photon has sufficient energy to form multiple electron-hole pairs through the process of secondary ionization by the primary photoelectron. An average of one electron-hole pair is liberated for each 3.68 eV of photon energy absorbed (this figure varies slightly with temperature). The charge liberated by single X-ray photons (~100-1000 electrons) is easily detectable if the amplifier noise is low enough. Therefore at X-ray energies CCDs can be used as photon counting detectors, with the measured signal charges proportional to the photon energies.

This use as an imaging X-ray spectrometer requires that no more than one photon is incident on each pixel in any image frame, which imposes a requirement that image collection times be limited to ~seconds for typical astronomical applications. In addition the signal charge must ideally be completely collected within the original pixel, transported to the output node without losses due to imperfect charge transfer efficiency (CTE), and measured without degradation by device readout noise.

Each of these requirements places special demands on the detector structure, and complicates the analysis of the data produced by the device. Charge collection efficiency is a function of the electric field strength at the site of X-ray absorption and is better in devices fabricated from higher resistivity material [Bautz et al, Hopkinson, Lumb et al]. Charge collection efficiency also improves as the pixel size increases. Even in high resistivity devices with large pixels, however, a sign)ficant fraction of all X-ray interactions will deposit charge in more than one pixel. A crucial consequence of imperfect charge collection is that not all detectable interactions yield useful spectroscopic information. Since the distribution of charge in a group of adjacent pixels is an indicator of the efficiency of charge collection [Bautz et al], maximum spectral resolution can only be obtained if a mutiplet of pixel values (usually a 3-pixel-by-3-pixel square neighborhood) is analyzed for each event [Lumb and Holland 1988a]. Moreover, as will be illustrated in Section 3.1, one can trade spectral resolution for detection efficiency by varying event analysis parameters. (Analysis of pixel multiplets also provides a means to discriminate between X-ray photon events and background events produced by high-energy particles. See section 3.3)

Charge transfer within a CCD is subject to inefficiencies caused by the trapping of signal charge at discrete sites in the silicon. These may be at crystalline defects or at sites with a defect introduced by a manufacturing or design error. The probability of trapping any signal depends upon many factors such as the temperature, clock rate and previous history of charge passing through the trap. In ground-based optical imaging applications there is often sufficient signal in every pixel due to photons from the night sky background that all traps remained filled, and they have a negligible effect on the image data. For X-ray photon counting applications, there is no such background, and the event arrival rate requirements noted above almost *guarantee* that traps will depopulate between the arrival of successive signal packets. Charge transfer losses therefore tend to be more severe for X-ray astronomy. The result is that even with a charge transfer inefficiency as low as 10-5 per pixel, charge packets traversing 1000 pixels will lose 1% of their signal, producing an apparent spatially varying gain function. In principle this is correctable, but the variation of the transfer losses with other parameters, particularly radiation damage, hinder this correction.