ASTRONOMICAL IMAGING APPLICATIONS FOR CCDS

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ABSTRACT

Preliminary testing of a back-illuminated, buried-channel CCD camera for astromical telescopic imaging applications has already demonstrated an enormous research potential for this device. Images of several planets and both galactic and extragalactic objects were obtained using a 400 x 400 element TI CCD in a JPL developed camera on the University of Arizona's 154 cm telescope on Mt. Lemmon. The high quantum efficiency and relatively low noise of this CCD, along with the inherently high photometric and geometric stability, opens up new opportunities for astronomical research, especially in the spectral range from 0.8 to 1.0 μm. For example, images of Uranus obtained in the 0.89 μm absorption band of methane clearly reveal for the first time markings on the disk of this remote planet. Applications for both ground-based and near-earth orbiting telescopes are discussed.

I. INTRODUCTION

Shortly after the 1965 NASA/JPL symposium on the technology and application of charge-coupled devices, we were successful in employing a thinned, back-illuminated, buried-channel CCD for telescopic imaging of astronomical objects. The results which we obtained are most promising, and suggest that CCD's will attain widespread use in astronomical research as soon as they become more readily available. The superior photometric characteristics of CCD's in the visible and far-red spectral regions give them a distinct advantage over other currently employed electronic detectors (such as SIT and SEC devices), especially where precise area photometry is desired. Although CCD's are presently unable to compete with photographic emulsions for their high-density, data-storage capacity, or with various other photodetectors for short-wavelength response, their special characteristics as applied to many current astrophysical problems assure them a major role in astronomical research over the coming decade, both from the ground and from space.

II. CHARACTERISTICS OF BACK-ILLUMINATED CCD'S

Those characteristics of the thinned, back-illuminated CCD which so intrigue the observational astronomer are, by no means, properties which are peculiar to astrophysical research interests alone. Nevertheless, I will call specific attention to them here because, in several instances, they represent major breakthroughs when compared to currently employed area detectors.

(a) Spectral Range - covers the visible spectrum and the far red out to 1100 nm. The extended red sensitivity at relatively high quantum efficiency opens up an important spectral region for studies of planetary atmospheres and strongly redshifted galaxies and QSO's.

(b) Quantum Efficiency - only slightly less than unity in the red and still very high in the far red. At 1000 nm the quantum efficiency is approximately 200 times higher than its only competitor, the S-1 photocathode.

(c) Dynamic Range - approximately 2700 from S/N = 5 to saturation. This is equal to 8.5 stellar magnitudes, the approximate brightness range of the stars in many globular clusters.

(d) Linearity - better than 3×10^{-4}. The CCD, therefore, can be used for more than just an imaging device; both linearity and stability combine to produce an excellent area photometer.

(e) Dark Current - negligible.

(f) Readout Noise - less than 10 electrons per pixel. The negligible dark current and low readout noise make the CCD a sky-limited detector throughout its spectral operational range. All other area detectors are noise-limited in the far red.

III. ASTRONOMICAL OBSERVATIONS

Preliminary testing of a thinned, back-illuminated CCD on an astronomical telescope began in April and May 1976 at the University of Arizona's Mt. Lemmon Observatory, 30 miles north of Tucson. The detector was a Texas Instruments 400 x 400-element, thinned, back-illuminated, buried channel CCD (JPL-11) incorporated into a breadboard camera* designed and fabricated by the Jet Propulsion Laboratory. Throughout the observing runs the CCD chip was cooled to 210°K by a thermostatically regulated flow of cold gas from a liquid-nitrogen Dewar. Although the camera system contained a 10-bit A/D converter, the recording of the CCD readout was limited to only eight of the ten bits (the most and/or least significant bit(s) could be dropped), and we were correspondingly constrained in the operational dynamic range.

The CCD camera was mounted at the f/13 Cassegrainian focus of the Mt. Lemmon 154-cm reflector. The f/13 focus has a focal-plane scale of 9.4 arcsec/mm, so that each 23 μm element (pixel) of the CCD array subtended an angle of 0.22 arcsec or a solid angle of 0.047 arcsec². The total array projected onto an area of the sky approximately 85 arcsec on the side. The breadboard camera had the capability for mounting optical filters, but contained no provisions for visual focusing. Although focusing could be and was accomplished by successive approximation using a 6-second readout display mode, the procedure was awkward and time consuming.

Two observing runs of approximately one week each were scheduled in mid-April and mid-May 1976. Unseasonable snows and poor image quality hampered the April run, but better conditions prevailed in May. A number of solar system and deep-space objects were recorded, primarily in several narrow spectral passbands in the far red, i.e., in the range from 800 to 1000 nm. Of particular interest are images of Uranus obtained in the 890 nm absorption band of methane. These images clearly reveal for the first time cloud structure high in the atmosphere of Uranus (Fig. 1). Until a CCD became available for far-red methane-band imaging of this remote planet, no features had ever been recorded (with any degree of confidence) on the tiny 4-arcsec disk. Although the analysis is still incomplete, the results indicate that Uranus possesses a thin cirrus-type cloud layer composed of methane-ice crystals and that the diameter of the planet is somewhat greater than was previously thought. The Uranus images were recorded at an exposure time of 2 minutes, quite long compared to the nominal exposures for typical planetary images. The reflectivity of Uranus in the 890-nm methane band, however, is less than 0.01 and thus presents a surface brightness too faint for other detectors to reach within reasonable exposure times. Other objects looked at during these observational tests were Saturn, Neptune, Comet West, a globular cluster (M3), a large elliptical galaxy with a jet (M87/Virgo A) and a QSO (3C273). Although some of the faint-object imaging was hindered by bright moonlight, we were very pleased with the observations of both solar system and deep-space objects and are anxious to try again under better observing conditions.

The brief astronomical tests carried out to date have already demonstrated the enormous research potential for CCD's in both groundbased and space applications. We will look now at the capabilities of this detector when used on large groundbased telescopes and on the orbiting Space Telescope (ST).

IV. FUTURE PROSPECTS

The future for CCD's in astronomical research is now well established, particularly (but not exclusively) in problems requiring imaging or area-photometry in the far-red regions of the spectrum. Although the device is competitive with other area detectors throughout the visible portion of the spectrum, I will direct my remarks to the region from 800 to 1100 nm, referred to variously as the "far red" by some, and as the "near infrared" by others. Figure 2 shows the signal-to-noise ratio for both stellar (S) and extended sources (E) in a 100 nm bandpass centered on 1000 nm and computed for 3000 second exposures with a large groundbased telescope (the 4-m telescopes of the Kitt Peak National Observatory) and the ST (a 2.4-m space telescope to be launched in 1983). The focal ratio of the 4-m telescope (4M) is f/8 and the ST is f/24. The brightness of stars and extended sources are given in visual magnitudes and visual magnitudes per square arcsecond, respectively. Differences in detectability of faint objects are related to relative aperture, focal length and resolution and to the fact that the night sky at 1000 nm is 75 times brighter as seen from the earth's surface than when viewed from space. The bright night sky in the far red is caused by primarily airglow emission from OH molecules in the earth's atmosphere.

Objectives for future astronomical research with CCD's include studies of the atmospheres of the outer planets using images obtained in narrow molecular absorption bands. Much of the emphasis would be placed on Uranus and Neptune,

*I should state very clearly at this point that the JPL camera was designed for use as a laboratory test instrument and was never intended for operation in the inhospitable environment of an astronomical observatory dome. The success of the operation can be attributed directly to Jim Janesik and Larry Hoveland of JPL, who accompanied the instrument to Mt. Lemmon.

about which so little is now known, but we would also include studies of the dynamical properties of the atmospheres of Jupiter and Saturn.

Among deep-space objects of interest, we would certainly want to include highly redshifted galaxies and quasi-stellar objects (QSO's). The extreme red sensitivity of the CCD is particularly important in this application. Figure 3 shows the redshifted energy curve of giant elliptical galaxies together with the quantum efficiency curves of the CCD and the S-20 photocathode (the quantum efficiency of the S-1 photocathode is too low to appear on this diagram). The redshift parameter, Z, is defined as:

$$Z = \frac{\Delta\lambda}{\lambda} = \left(\frac{1 + v/c}{1 - v/c}\right)^{\frac{1}{2}} - 1$$

where λ equals wavelength, v is the recession velocity and c the velocity of light. Note that the S-20 photocathode does not retain adequate response in the far red to record giant elliptical galaxies redshifted beyond Z = 0.5. This is a serious limitation for those who want to study the very fringes of our universe.

The two areas of astronomical interest given above are only examples of the research problems in which one could use CCD detectors to excellent advantage. Many other problems of current astrophysical concern could be similarly identified, e.g., spectroscopy of highly redshifted objects.

The astronomical research in which CCD's will play a large role can be and, undoubtably, will be done with large or moderate-size groundbased telescopes. However, many of those studies which will be worked from the ground can be done better with a space telescope orbiting above the earth's atmosphere. Not only will angular resolution be higher than can be achieved under the very best conditions at the earth's surface, but the airglow of the night sky, which severely limits observations in the red beyond 800 nm, will be absent. I would hope that a CCD camera would be included as a prime instrument when NASA places the first large space telescope (ST) in orbit in 1983.

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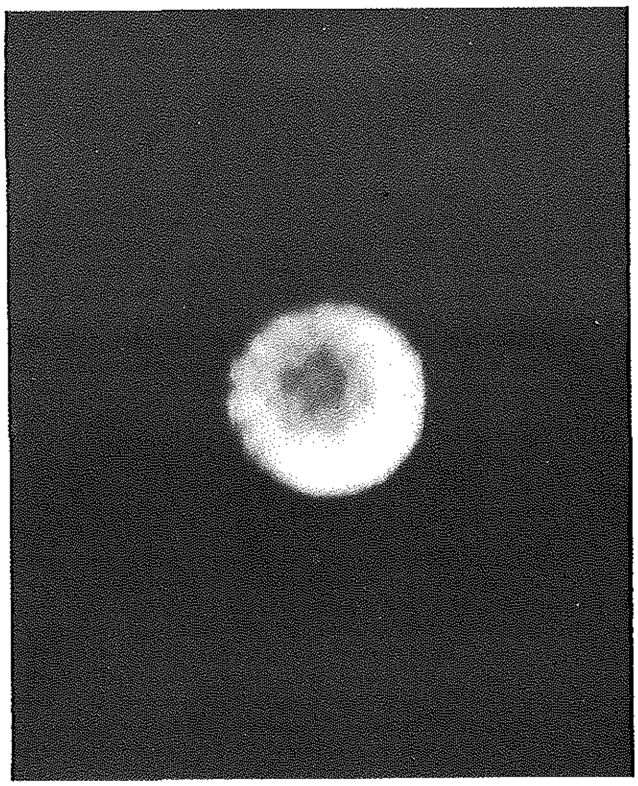

Fig. 1. Uranus in the 890-nm CH_4 absorption band.

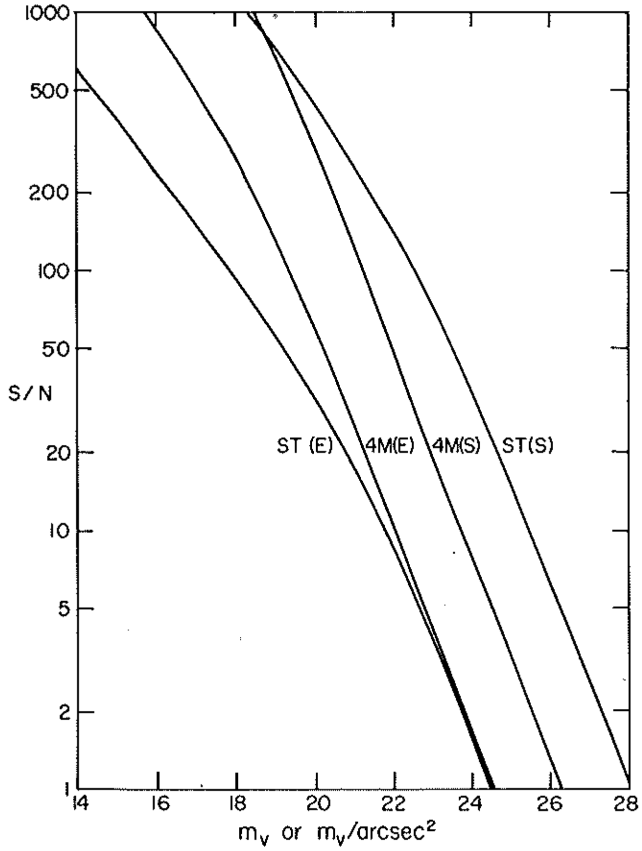

Fig. 2. S/N for stellar and extended sources exposed for 3000 seconds at 1000 nm (Δ = 100 nm) with a 4-m telescope and Space Telescope (see text).

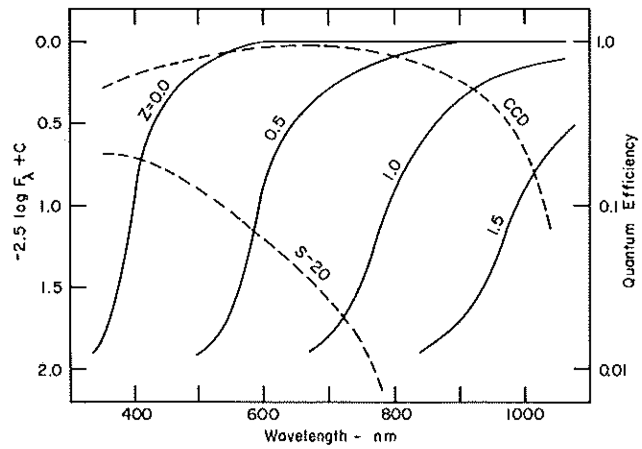

Fig. 3. Energy curves for redshifted giant elliptical galaxies and quantum efficiencies for CCD and S-20 photocathode.