# Charge Caching CMOS Detector for Polarimetry ($C^3$Po)

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## ABSTRACT

$C^3$Po is a concept for a novel array detector concept that is optimized for highly sensitive and precise differential imaging such as needed for astrophysical polarimetry. Chopping between two or more independent image states (such as four linearly independent polarization states) can be performed at speeds in the kHz domain to provide virtually simultaneous images without the need to read out the array at kHz frame rates. This allows the technology to be applied to large arrays with precise, slow readouts. All independent image planes are observed with the same physical pixel on the detector, which renders normalized differences between image planes insensitive to the gain of individual pixels. The detector concept has 100% geometrical fill factor and a quantum efficiency approaching unity. The technology can be applied to silicon to cover the 200-1100 nm wavelength range, and to infrared-sensitive materials such as HgCdTe or InSb for the 1-20 µm wavelength range. While the detector concept has a wide range of potential applications outside of astronomy, we focus here on its application to polarimetric observations of the Sun.

Keywords: Differential imaging, polarimetry, CMOS hybrid array, focal plane array, imaging lock-in amplifier

## 1. INTRODUCTION

Differential imaging can be done in two fundamentally different ways. One approach is a temporal modulation where one chops between various states (of polarization, for instance). However, the chopping has to be performed at a rate that is considerably faster than changes in the image such as fluctuations of the Earth's turbulent atmosphere or due to evolution of the object itself, which can be several 100 Hz in the case of seeing. Temporal modulation has the advantage that the different states are observed with the same detector elements (pixels), which makes normalized differences of image states independent of the spatially varying detector gain. However, the required high frequency is hard to achieve with large array detectors because they cannot be read out quickly enough.

Another approach consists in measuring the states strictly simultaneously by using an appropriate beam splitter arrangement. This has the advantage of being applicable to standard, large-scale but slow array detectors. On the other hand, differential geometric aberrations between the two (or more) beams as well as spatial gain variations introduce substantial systematic errors.

Most precise astronomical polarimeters use a combination of spatial and temporal modulation to combine the advantages of the two approaches. However, even a combination of spatial and slow temporal modulation cannot avoid a substantial influence of noise due to the temporal variation of the Earth's atmosphere. To avoid such systematic limitations, temporal modulation well above typical seeing frequencies are required.

In large solar telescope projects such as THEMIS, GREGOR, and ATST, particular attention has been paid to make the telescopes suited for polarimetry. However, since these telescopes are compact, the polarization measurement has to be performed early in the optical train, and it is very cumbersome to transfer two beams through the rest of the telescope (e.g. THEMIS), in particular when adaptive optics is involved. The best way to achieve highly precise differential imaging with these large telescopes is the use of fast temporal modulation alone.

For the ultimate precision in differential imaging, it is indispensable to modulate and demodulate the signal quickly. For astronomical polarimetry, this means at 1 kHz and higher frequencies, in particular when adaptive optics is involved.

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However, the required modulation frequencies are incompatible with large, scientific array detectors. Various schemes to deal with this issue have been proposed in the past (see Section 2). Array detector technology has now advanced to the point where the ideal detector for such applications could be realized based on CMOS hybrid technologies.

The idea for $C^3$Po occurred to me in the spring of 2001 while working with Rockwell Scientific on their HyViSI cameras for the SOLIS project. David Elmore suggested the name $C^3$Po in April 2002. I first published the ideas behind the $C^3$Po in 2003[1, 2]. This paper summarizes my current knowledge of this technology.

## 2. DESIGN HERITAGE

A breakthrough in imaging polarimetry was achieved by Povel[3] and colleagues with the first generation of Zurich IMaging POLarimeters (ZIMPOL I). The ZIMPOL I CCD array detector is alternately divided into photosensitive rows and storage rows that are shielded from light by a mask (see Fig. 1). The photo charges generated in the photosensitive rows during the first modulation half-cycle are shifted into the left storage row at the transition to the second modulation half-cycle. The photo charges generated during the second modulation half-cycle are shifted into the right storage row at the transition to the first modulation half-cycle. This is repeated over many modulation cycles, and the respective charges are integrated alternately and synchronously to the modulation. Whenever the desired amount of charges have been accumulated, the charges are read out. To avoid a reduction of the measured modulation amplitude by effects due to the finite transfer time of the charges from photosensitive to masked rows and vice versa, the transfer time must be about a factor of 100 faster than the modulation frequency.

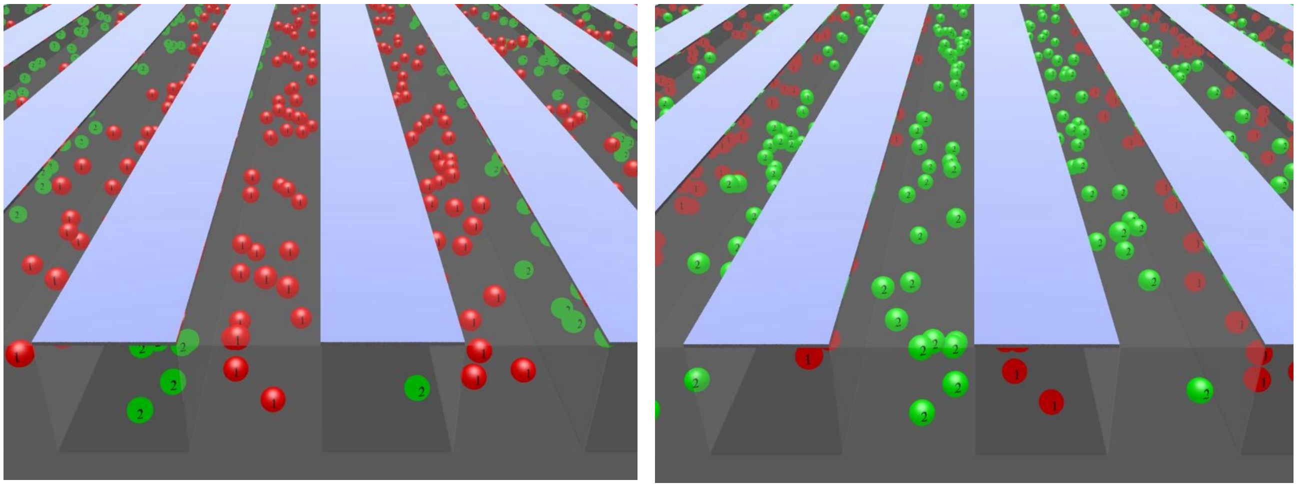

**Fig. 1** Operating principle of the ZIMPOL I scheme where charges are shifted below a mask in synchrony with the modulation. The left image shows the first half of the modulation phase where charges corresponding to this first half (labeled '1') are created and charges from the second half of the modulation cycle ('labeled '2') are stored behind the opaque mask. The right image shows the second half of the modulation cycle where charges from the first half have been moved below the mask and charges corresponding to the second modulation half are created.

ZIMPOL I is based on 42-kHz polarization modulation with piezoelastic modulators and custom 393 by 284 pixel CCD sensors[3]. It can operate up to four cameras simultaneously at a rate of up to 10 frames per second. This enables precise polarization measurements even with the short exposure times required for speckle imaging. The modulation rate is well also above typical frequencies of adaptive optics systems. ZIMPOL I has provided a wealth of scientific results on solar polarization thanks to its high sensitivity that reaches down to a few times $10^{-6}$. Because of its fast read-out rate and high modulation frequency in the 100-kHz range, ZIMPOL I has been the premier instrument for solar polarimetry coupled with image reconstruction techniques and behind adaptive optics system.

Drawbacks of ZIMPOL I include the low efficiency due to the mask (a factor of 2) and the restriction of a single CCD demodulator to one frequency (a factor of 3 for vector-polarimetry). ZIMPOL II[4] overcomes this total efficiency loss of a factor of 6. Four sampling intervals in one modulation cycle are needed to record all four modulation states associated with the four Stokes parameters describing polarized light. The light is focused on the CCD with a micro-lens array such that out of four pixels in one column only one is used for light detection while the remaining three are used for temporary charge storage. In this way all four Stokes parameters may be measured with a single CCD sensor. While possible, it proved hard to accurately align the micro-lenses on the CCD[5]. Furthermore, stray-light within the micro-lens-CCD assembly led to significant problems during the data reduction. Also, it has not been possible to adapt the scheme to a backside-illuminated CCD that would have provided the desired high quantum efficiency because the alignment accuracy between the pixel structure and the mask is much higher than what can be done in current CCD backside processing. And finally, the strong dependence of the ZIMPOL scheme on the charge storage and transportation scheme of CCD made it impossible to adapt it to infrared detectors.

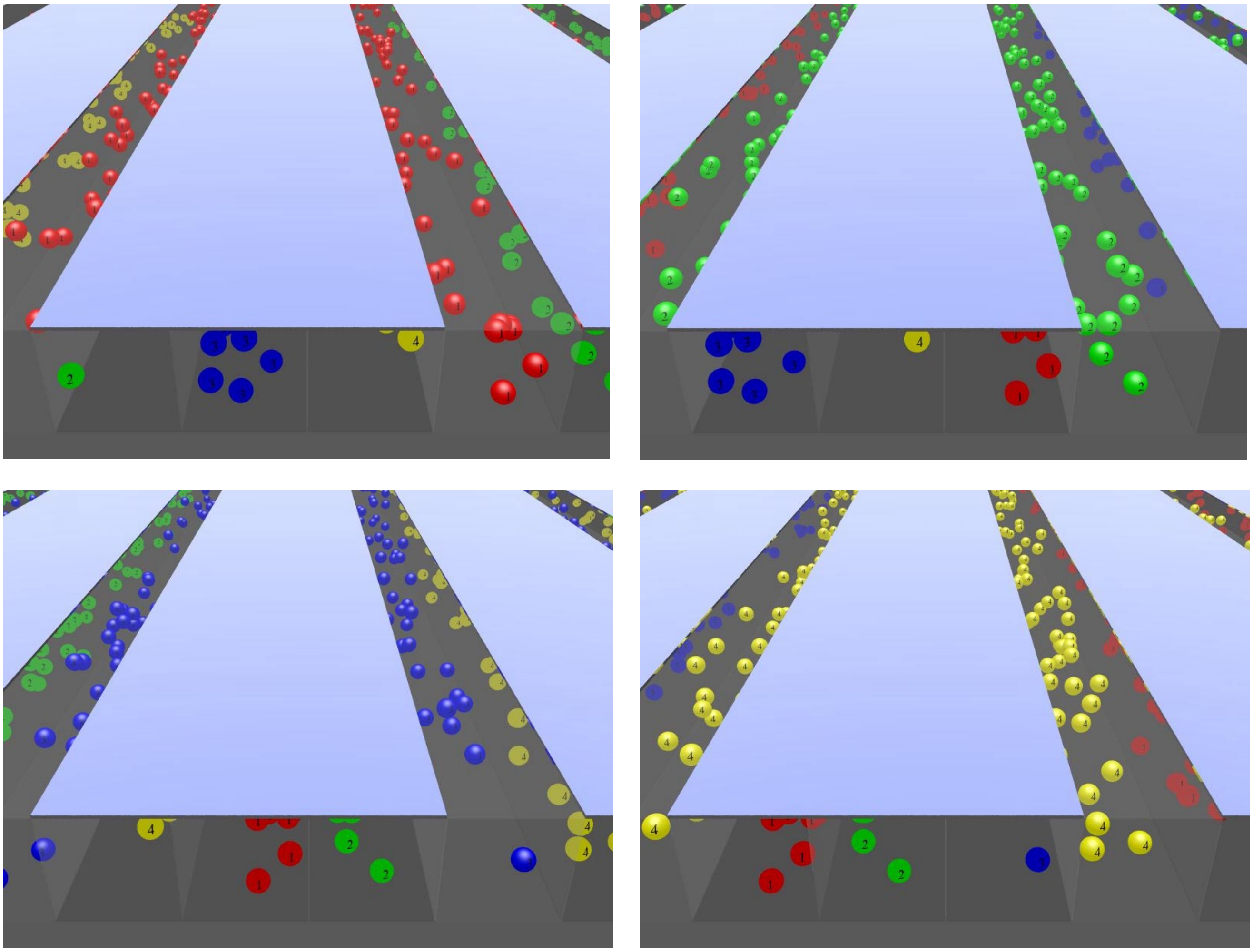

**Fig. 2** Operating principle of the ZIMPOL II scheme where charges are shifted below a mask in synchrony with a modulation that has four distinct phases such as needed to modulate all four Stokes parameters. The corresponding charges are labeled 1 to 4. In contrast to ZIMPOL I, there are now three covered rows for every exposed row. The four images show the four modulation phases where the corresponding charges are accumulated.

Despite these drawbacks, the ZIMPOL II scheme has been successfully expanded into the ultraviolet range of the spectrum with a CCD that has masked storage rows that are considerably narrower than the exposed rows whose ultraviolet sensitivity has been boosted by making holes in the electrodes of the front-side illuminated CCD[6].

## 3. CMOS HYBRID IMPLEMENTATION

New developments in hybrid detector arrays have opened the possibility to build the perfect array detector for polarimetry as envisioned by Lites[7]. The basic idea consists in combining the versatile CMOS technology with the sensitivity of backside-illuminated detectors. Such detectors have been developed for infrared focal-plane arrays where an infrared-sensitive material (such as HgCdTe or InSb) is bonded to a CMOS multiplexer. Such an approach can also be used in the visible. The HyViSI hybrid CMOS silicon focal-plane arrays from Rockwell Scientific combine the advantages of a backside-illuminated CCD with the flexibility, speed, and cost efficiency of a CMOS imager. The HyViSI arrays are based on the same CMOS hybrid technology as the well-known Rockwell infrared arrays. Silicon is used instead of HgCdTe, which makes the arrays sensitive to visible and ultraviolet light. The same read-out multiplexer can be used for either infrared or HyViSI arrays. 1024 by 1024 pixel HyViSI cameras are available as a commercial product and have seen their first application in solar observations[8].

A typical CMOS multiplexer used in infrared hybrid and the Rockwell HyViSI arrays contains two capacities, one of which is used for integrating the charges of the current exposure, while the other holds the charges from the previous exposure that is concurrently read out. Instead of only 2 capacities, a $C^3$Po has typically 8 capacities within every pixel to hold 4 separate image states (corresponding to linearly independent combinations of Stokes parameters). $C^3$Po arrays with 16 capacities could be envisioned to operate with polarimeters based on rotating retarders, which require the accumulation of 8 different states. $C^3$Po arrays with only four capacities could be useful if only a single polarizer Stokes parameter is measured as well as for many other applications as discussed below. In the rest of this chapter, a $C^3$Po with 8 capacities for four different image states will be considered.

In addition to increasing the number of capacities per pixel, there is also a charge distribution circuit that sends the electrons from the photosensitive layer to the integrating capacities in synchrony with the modulation of the incoming light. Before the next image is exposed, the four integrating capacities would transfer their charges to the four read-out capacities. The read-out circuit will also be more complex than a conventional CMOS multiplexer because several capacities per pixel need to be read out. Figure 3 shows an outline of one pixel of such a $C^3$Po that can integrate four different image states or modulation phases and would be ideally suited for polarimetry with liquid crystal polarization modulators.

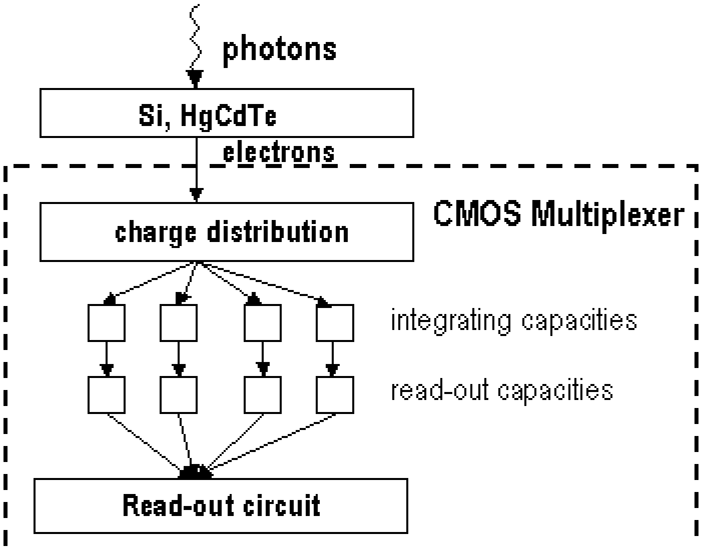

**Fig. 3** Schematic layout of a single pixel of a $C^3$Po array detector that is capable of measuring all four Stokes parameters. It has a 100% geometric fill factor and very high quantum efficiency. The photosensitive layer can be chosen to cover almost any spectral region between 200 nm and 20 µm.

Since a typical 18-µm CMOS multiplexer pixel can provide capacitance to hold about 6,000,000 electrons, a full-well depth of more than 500,000 per modulation state would still be feasible for every 18-µm pixel. Larger pixel sizes would offer even larger full-well depths per state. The multiplexer could be hybridized with either silicon to cover the 200-nm to 1100-nm wavelength range, or with HgCdTe to cover the infrared wavelength range.

Figure 4 shows a graphical representation of the operating principle of a four-state C$^3$Po. Electrons generated by light from a certain modulation state are labeled `1’ to `4’. Conducting material allows those electrons to flow from the photosensitive layer to the CMOS multiplexer where they are accumulated in the corresponding capacities. Figure 4 does not show the readout capacities.

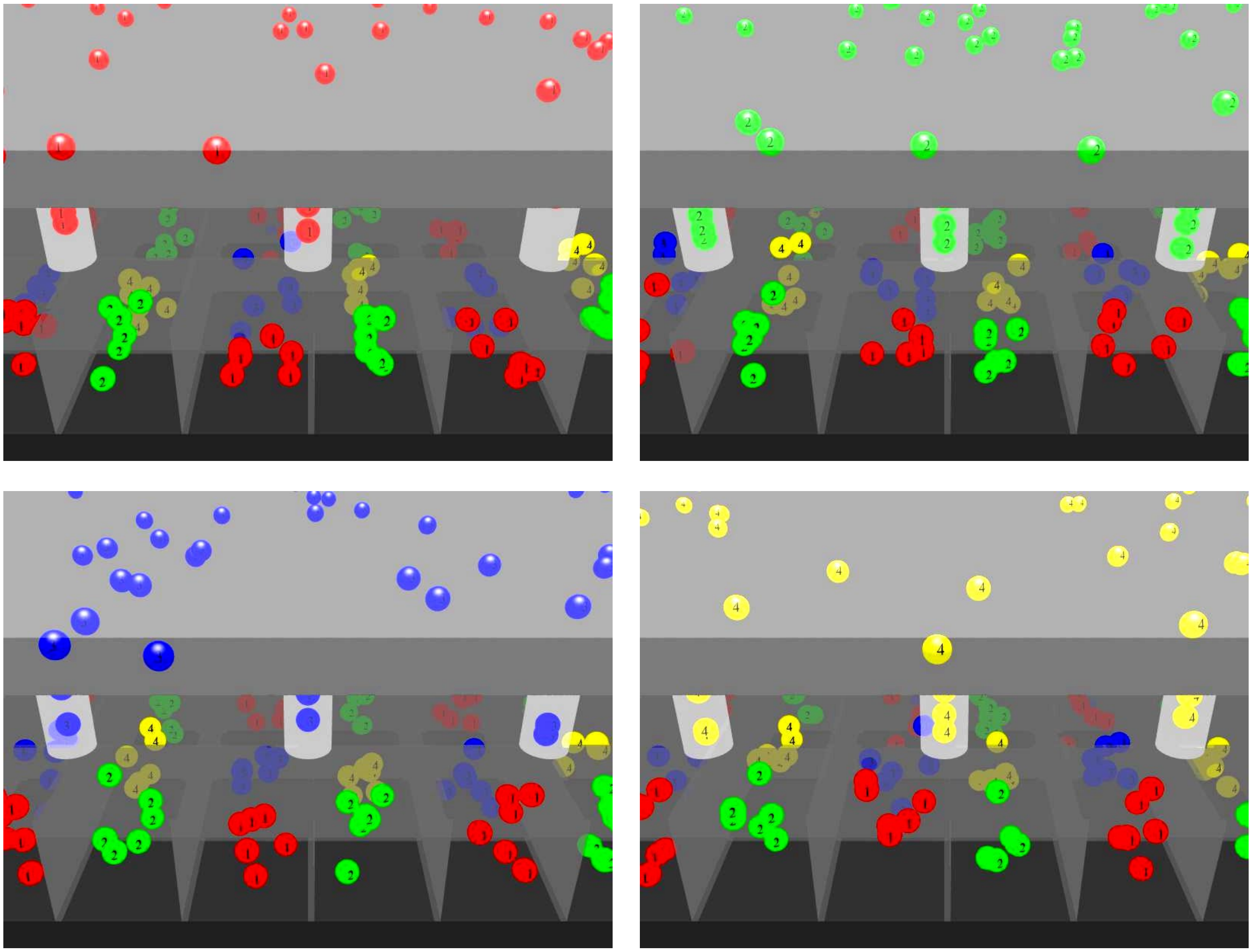

**Fig. 4** Schematic operating principle of a C$^3$Po detector that is capable of measuring all four Stokes parameters. During each of the four modulation phases, the photosensitive layer generates charges and sends them to one of the four charge storage cells present in each pixel. For simplicity, the read-out capacities are not shown.

C3Po has a number of important advantages over the ZIMPOL II scheme which are summarized in Table 1.

**Table 1:** Comparison of the ZIMPOL II and C$^3$Po concepts.

| | **ZIMPOL II** | **C$^3$Po** |
|---|---|---|
| Geometric fill factor | <25% | 100% |
| Peak quantum efficiency | <35% | >85% |
| Wavelength coverage | 200 - 1100 nm | 200 - 20,000 nm |
| Full-well depth | 250,000 | >500,000 |

Discussions on a C$^3$Po development for solar polarimetry in the visible part of the spectrum have progressed to the point where draft requirements for such a focal plane array have been developed. Table 2 lists these requirements with brief explanations. Many of the requirements are based experience with the 1024 by 1024 HyViSI cameras purchased for the SOLIS Vector-Spectromagnetograph[8].

**Table 2:** Draft requirements for a C$^3$Po implementation.

| **Item** | **Specification** | **Comments** |
|---|---|---|
| Format | 1024 by 1024 pixels | 2048 by 2048 preferred |
| Pixel pitch | 18 micrometers square | Larger pixels would hold more charges |
| Number of image states | 4 | 2 is the absolute minimum, 8 for rotating waveplate |
| Full well depth per image state | >500,000 e | More would be better |
| Geometric fill factor | 100% | No incident photons blocked |
| Frame rate | >= 10 frames per second | goal of 25 frames/s |
| Modulation rate | > 1 kHz | Charge distribution at 4 kHz |
| Readout/exposure mode | Snapshot | |
| Charge transfer time | < 5% of modulation period | To avoid smearing between image states |
| Dynamic range | >10000 | Full well / readout noise |
| Readout noise | <300 e rms per pixel | goal of <150 e; well below photon shot noise |
| Quantum efficiency | >85% @ 630 nm<br>>85% @ 854 nm<br>>5% @1083 nm | at operating temperature |
| QE uniformity | <3% std dev/mean | Excludes etalon fringing |
| Operable pixels | >98%; no dead rows or columns | In region of interest |
| Linearity | Better than 1% over full range | Deviation from best fit line |
| Dark current | <5000 e per sec per pixel @ -15C | |
| Dark current stability | Better than 300 e/s/pixel rms over 12 hours | |
| Flatness | <100 micrometer peak-peak | |
| Image lag | <0.2% | Signal remaining from previous frame |
| Channel crosstalk | <0.1% | Leakage of inter-channel signals |
| Row and column modulation transfer functions | >0.96 @ 5 cycles per mm<br>>0.91 @ 10 cycles per mm<br>>0.73 @ 15 cycles per mm<br>>0.56 @ 20 cycles per mm<br>>0.40 @ 25 cycles per mm | At wavelengths 630, 854 and 1083 nm (Nyquist frequency is 27.8 cycles per mm) |

## 4. OTHER POTENTIAL APPLICATIONS

Any imaging application that requires the extraction of a small difference between sequential images would gain significantly from a $C^3$Po implementation. The implementation could be tailored to the specific application. Here I list a few potential applications.

Apart from polarimetry, observations that need to chop quickly in wavelength would also gain significantly from such a device. An example would be the observation of solar coronal emission lines. By switching between the coronal emission line and the nearby continuum, the solar corona can be observed even under less than favorable sky background conditions. Since much of the sky background is due to fast-moving dust specs, rapid switching between two or more wavelength bands is required for accurate background suppression. Figure 5 shows an image of the solar corona obtained under very high background conditions using 100 kHz wavelength chopping and the ZIMPOL I detector system.

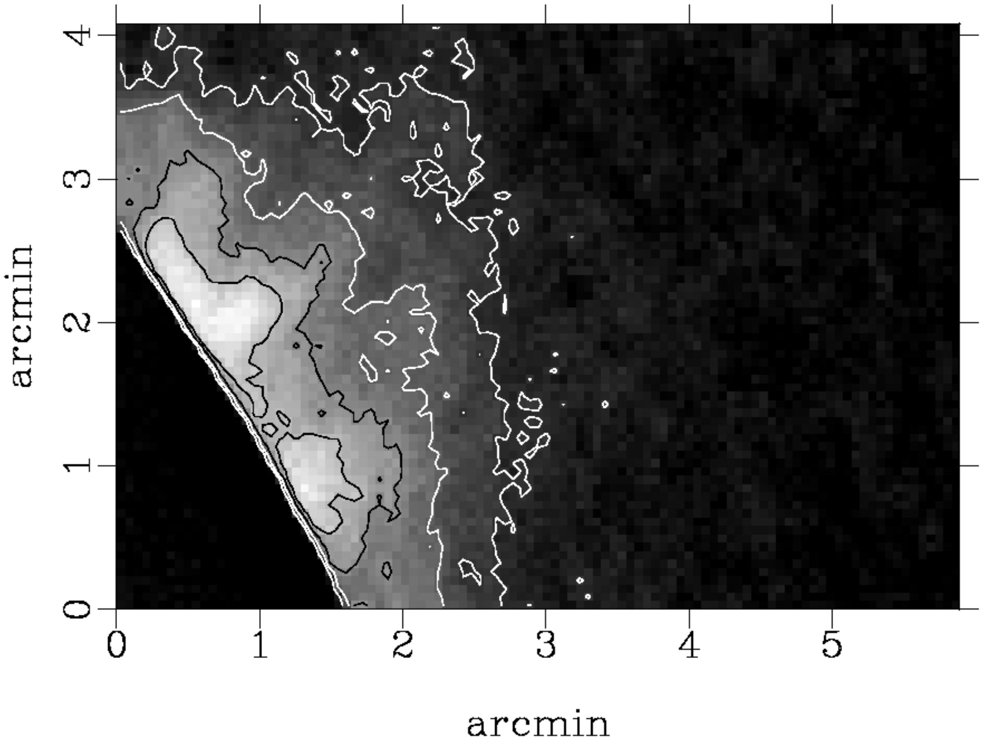

**Fig. 5** The solar corona above 1.4 solar radii as seen in the red line of FeX 637.54 nm. The median sky background was $280*10^{-6}$ of the disk center brightness. The faintest detectable coronal signal was $1.5*10^{-6}$. Contour lines are drawn at 1.5, 3.0, 4.5, and $6.0*10^{-6}$. The image is based on 100-kHz wavelength modulation between the coronal line and the near-by continuum[9].

Another astronomical application for a two-state $C^3$Po is in the area of curvature wavefront sensing for adaptive optics. Curvature wavefront sensing analysis two images of a point source that are equal amounts away from the focus, but on opposite sides. One way to obtain these two images consists in rapidly changing the focus location of the wavefront sensing beam. A two-state $C^3$Po could then be used to integrate two image planes corresponding to the two out-of-focus images. Similarly, to record microscope images of rapidly evolving objects as a function of focus depth or wavelength, a $C^3$Po would be the ideal detector.

A more general application for a $C^3$Po detector is in the area of three-dimensional range imaging where the `image' contains information on the distance (or range) of the objects from the camera. A modulated light source illuminates the scene, and the detector measures the phase delay between the light source and the reflected light. The phase delay is a linear function of the distance between the light source and the object. The modulation frequency defines the range over which a unique distance can be determined. Experimental cameras based on specialized semiconductor technology with a few thousand pixels have been demonstrated[10]. Typically four sampling intervals with a single modulation period are used, which is equivalent to measuring four polarization states as discussed above. To reduce the optical power requirement for the modulated light source, integration of the signal over many modulation periods is required, which is again what is required for accurate polarimetry. A modulation rate of 1 MHz provides an unambiguous range of 150 m. A $C^3$Po would therefore be able to demodulate at a 1 MHz rate or faster to be useful as a range detector.

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