A Hard X-Ray Imaging Polarimeter for Balloon-Borne Astronomy

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Abstract

A polarimeter based upon an optical avalanche chamber is being developed at the Marshall Space Flight Center. The polarimeter will be carried aloft by balloon for imaged polarization measurements of celestial sources at energies between 40 keV and 100 keV. In the lab, using a small prototype polarimeter, we have measured a modulation factor of 0.3 at 54 keV. The polarimeter works by using a CCD camera to image the track of each photoelectron liberated when an x-ray is absorbed in the optical avalanche chamber. By virtue of this technique, we are able to measure the ejection direction of the photoelectrons (i.e. polarization of the incident x-ray beam) as well as locate the position of the absorbed x-ray to within a region smaller than the size of the charge cloud. As a result, we can obtain a map detailing the two dimensional distribution of polarization amplitude and polarization direction. We will present details of this work as well as a description of the balloon experiment we are currently building.

I. INTRODUCTION

Polarization analysis of celestial x-ray sources has long been of interest to astronomers since it has the potential of revealing many details about the magnetic fields, source geometries, and emission mechanisms found in x-ray sources such as pulsars, binary x-ray sources powered by accretion, black hole candidates, and active galactic nuclei. More recently, with the development of strong polarized x-ray sources utilizing synchroton emission and channeling radiation, polarization analysis has taken on a heightened priority among reseachers in solid state physics.

Up to now, polarization measurements have been made almost exclusively with Bragg crystal or Thomson scattering polarimeters. In fact, the only definitive measurement of polarized x-rays from a celestial source was made two decades ago using a Bragg crystal polarimeter flown on board the OSO-8 spacecraft[1]. This measurement established that there exists a 19% linear polarization from the Crab Nebula at 2.6 keV and 5.2 keV.

A drawback of the polarimetry techniques mentioned above is their inability to simultaneously combine imaging with polarization measurement, and in the case of the Bragg crystal polarimeter, only narrow bands of energy can be analyzed. Recently two techniques which combine polarimetry with imaging have been discussed in the literature. Both techniques rely on the correlation between incident polarization and photoelectron ejection direction. The first of these, the "pixel polarimeter", obtains polarization information from the pixels crossed by a photoelectron that has been liberated by the absorption of an x-ray in the substrate of a silicon CCD. The feasibility of this technique has been demonstrated and reported in the literature by Tsunemi et al[2] and Buschorn et al[3]. A second method, developed by us, utilizes an intensified, UV sensitive CCD camera in combination with an optical avalanche chamber to image photoelectron tracks and thereby measure polarization[4].

Two years ago, we presented our early conception of an instrument, based upon an optical avalanche chamber, which we intended to build for balloon-borne x-ray polarimetry[5]. In this paper we will summarize past work and give the current status of the Marshall Space Flight Center (MSFC) hard x-ray imaging polarimeter. Henceforth this instrument will be referred to by the acronym XIMP for **X**-ray **IM**aging **P**olarimeter - pronounced like CHIMP.

II. OPERATING PRINCIPLE

When the absorption of an x-ray photon liberates an electron from the K-shell, the ejection direction of the photoelectron lies preferentially in the direction of the electric field of the incident radiation. If the the radiation is polarized, photoelectrons will be ejected along the polarization direction with a distribution strongly peaked in the direction of the radiation's electric field. By measuring the ejection direction of an ensemble of photoelectrons, one can determine the degree and direction of polarization for the incident radiation

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To be able to measure x-ray polarization we developed a technique whereby an intensified CCD camera is used to image photoelectron tracks made visible in an optical avalanche chamber. Figure 1, below, contains a schematic of our prototype XIMP.

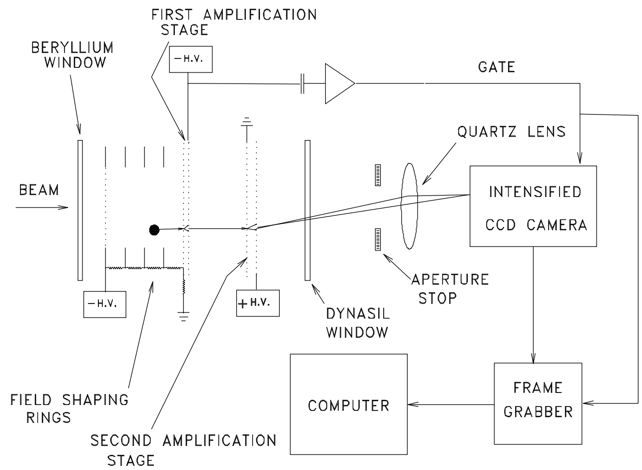

Figure 1. A schematic view of the hard x-ray polarimeter prototype.

III. LABORATORY PROTOTYPE

An early incarnation of our laboratory prototype has been described in the reference 1. The basic scheme is unchanged (refer to figure 1). It consists of an intensified, UV-sensitive CCD camera coupled to a two stage optical avalanche chamber. The charge signal from the first amplification stage is used to provide a TTL trigger pulse to the image intensifier which is coupled to the CCD camera. Given the 3 cm separation between amplification stages, the transfer field is chosen to provide a rapid transfer of charge to the second stage; the transfer time is approximately 1μs: this allows little diffusion of the charge cloud to occur while providing adequate time to trigger the camera (>500 ns). The width of the trigger pulse determines the length of the exposure and is chosen to be 50 μs; this is more than enough time to collect all the light produced at the second stage, but greatly reduces the amount of unwanted light coming from tiny light leaks and scintillation light coming from events with energies lying outside the threshold set by the upper and lower level discriminators.

The current protoype is shown in the photo (figure 2). Recent changes are in the increased absorption depth: formerly 5cm now 50 cm and a reduced magnification factor: now 0.06, reduced from 0.2. These changes were made to simulate with high fidelity the flight version of XIMP with minimal change in existing prototype hardware. We also chose to upgrade the data acquisition system which now consists of a Analogic DASM™-FGM SCSI real-time video frame grabber and an IBM RISC computer. Some salient features of the current version of the prototype XIMP are given in table 1 below.

Figure 3 contains an image of a photoelectron track imaged by the current prototype polarimeter system. The photoelectron was ejected following the absorption of a 60 keV x-ray from an ^{241}Am source.

Table 1. Important parameters of the prototype XIMP.

Type of gas detector	Two-stage optical avalanche chamber.
Depth of absorption/drift region	50 cm
Distance separating amplification stages	3 cm
Detection medium	98% argon + 2% trimethylamine ($(CH_3)_3N$) at 2 atm pressure.
Optical system	Dynasil™ UV transmitting window, fused quartz plano convex lens - F1, 3 mm focal length. Magnification factor: 0.06
Camera	ITT model F4577-10012 intensified gated CCD camera - 488 V x 754 H pixel resolution
Data acquisition	Analogic DASM™-FGM SCSI real-time video frame grabber. IBM RISC computer

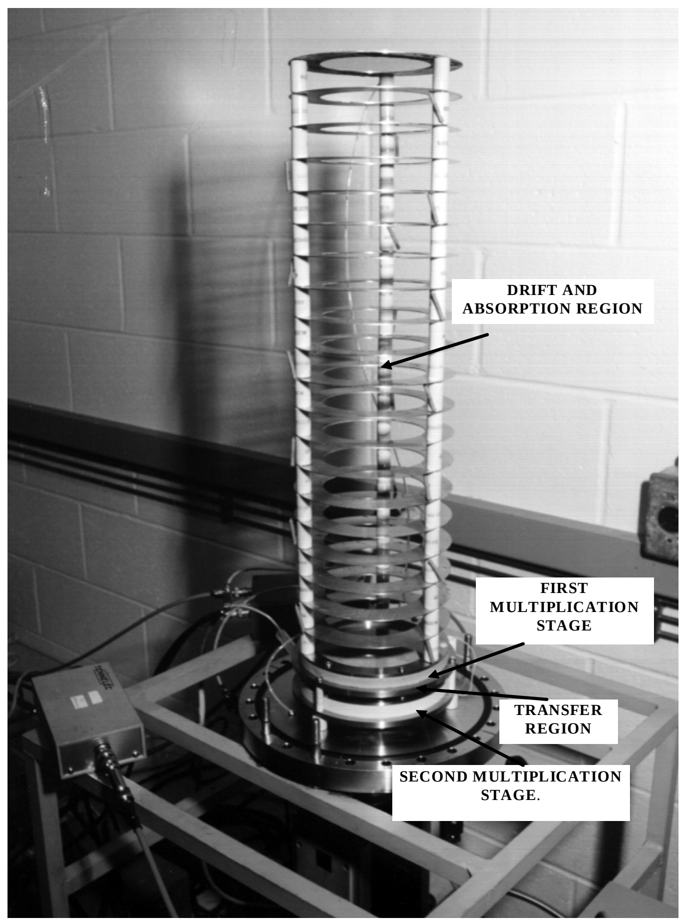

Figure 2. A photograph of the prototype hard x-ray imaging polarimeter. The pressure vessel has been removed to show interior details.

Using the original prototype XIMP, analysis of a 92% polarized x-ray beam gave encouraging results. When a polarized x-ray beam was shone into the polarimeter, and the ejection direction of more than a thousand photoelectrons were accumulated into a histogram, we obtained the curve shown in figure 4. From this curve we determined the depth of modulation or modulation factor which characterizes the sensitivity of this instrument. At 54 keV we measured a modulation factor of 0.3. Though we were initially concerned that the increased electron cloud diffusion in the 50 cm depth - an increase in rms diffusion width by a factor of $\sqrt{10}$ - may reduce the modulation factor slightly, preliminary results indicate this is not the case. More data is needed to confirm this, however.

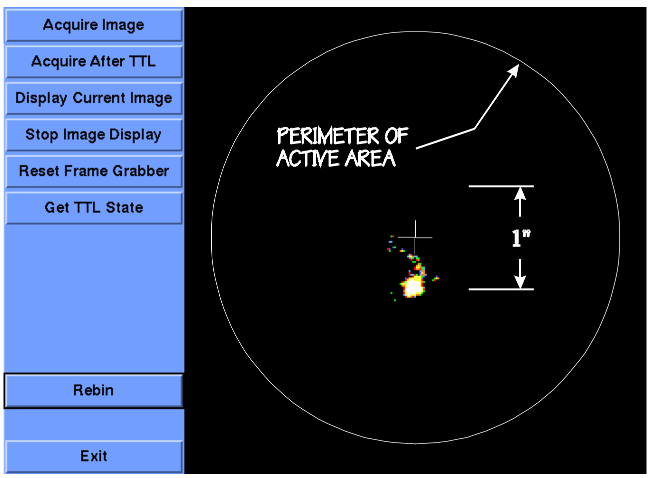

Figure 3. An image of a photoelectron track ejected following the absorption of a 60 keV photon in the hard x-ray imaging polarimeter prototype.

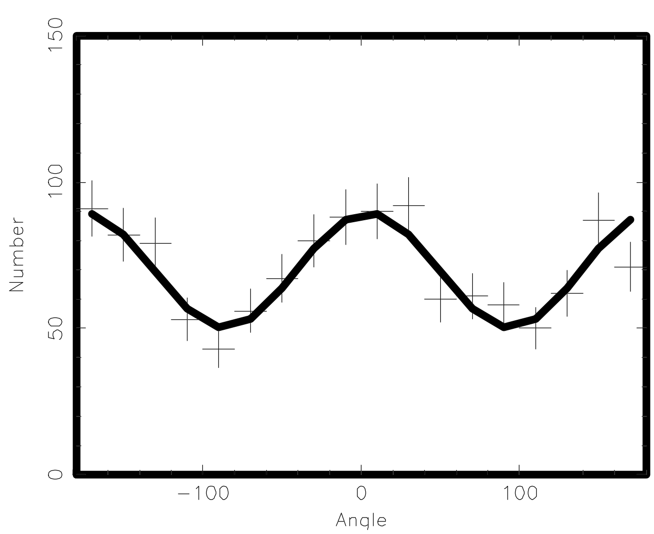

Figure 4. The distribution obtained by plotting the ejection direction of photoelectrons emitted following the absorption of polarized x-rays in the prototype polarimeter.

IV. FLIGHT INSTRUMENT DESIGN

A scaled up version of our laboratory prototype polarimeter (i.e. XIMP) is currently being built at the Marshall Space Flight Center. When carried aloft by a high altitude balloon to altitudes greater than 120,000 ft., it will measure the polarization of strong celestial sources of x-rays such as the Crab Nebula and Cygnus X-1 in the energy range: 40 keV - 100 keV. A schematic diagram of the polarimeter is shown in figure 5.

A. Data Acquisition System

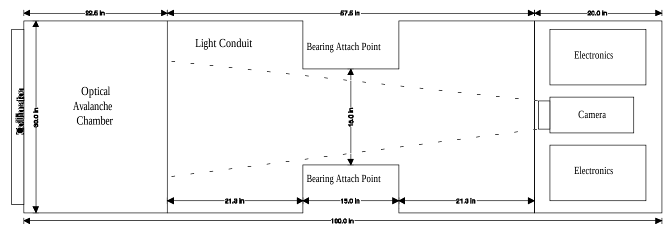

Figure 5. Schematic representation of the MSFC hard x-ray imagining polarimeter.

The schematic shown in figure 6 reveals the layout of the data acquisition system. Though an enormous amount of video data will be collected ($3.0x10^6$ bytes per second), thresholds on pixel brightness are set in hardware to sift out the mere thousand or so pixels representing the photoelectron track image. Pixel locations and values will be simultaneously stored on tape and relayed to the ground. The photo in figure 7 shows the bulk of the electronics which will be flown and reveals the electronic simplicity of this scheme. Principle features of the MSFC hard x-ray imaging polarimeter are summarized in table 2.

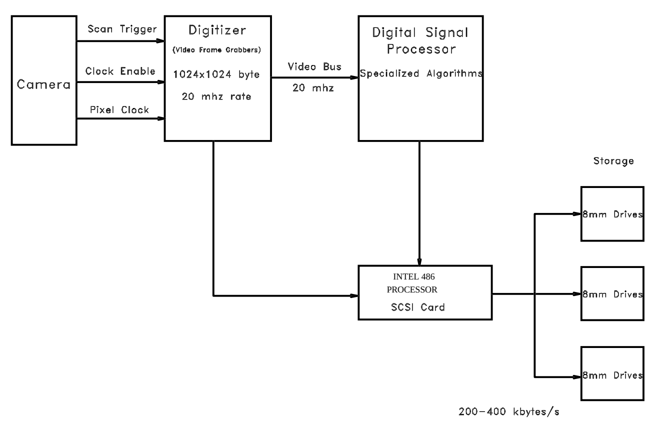

Figure 6. A schematic diagram of theXIMP data acquisition system.

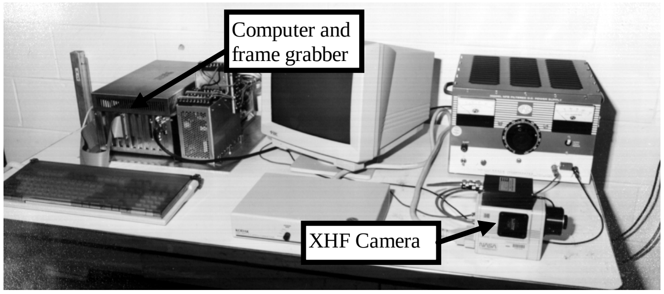

Figure 7. The simplicity of the XIMP data acquisition system is revealed in the above photograph. Shown are the Kodak XHF camera and its controller, the electronics box containing the Hyperspeed XM860-5116 ISA bus I860 supercomputer board (video frame grabber) and the Intel 486-based computer. Other items shown: the video monitor, keyboard, and DC power supply are for in the lab operation only.

Table 2. Important parameters of prototype hard x-ray polarimeter.	
Type of gas detector	Two-stage optical avalanche chamber.
Sensitive area	1000 cm^2
Depth of absorption/drift region	50 cm
Distance separating amplification stages	3 cm
Electrical breakdown suppression	A scheme to eliminate electrical breakdown on the second amplification stage utilizing a gated, pulsed high voltage supply to provide transfer voltage.
Detection medium	98% argon + 2% trimethylamine ($(CH_3)_3N$) at 2 atm pressure. Mixtures with higher concentrations of trimethylamine may be used.
Optical system	Dynasil™ UV transmitting window, three component UV lens system. Tapered fiberoptic coupling between image intensifier and CCD. Overall magnification factor: 0.025
Camera	Kodak Megaplus XHF CCD camera with 1024x1024 pixels, non-interlaced operation, 30 frames per second. The CCD is coupled via tapered fiber optic coupling to a 25mm PP0340 GEN II UV sensitive image intensifier allowing gated operation.
Data acquisition	Hyperspeed XM860-5116 ISA bus I860 supercomputer board. Intel 486 microprocessor.
Rotation	Approximately 1 RPM rotation about optical axis to average out potential sources of systematic error.

B. Optical System

The demands imposed on the optical system to be used with XIMP are quite severe. To have an effective polarimeter, we require a very fast optical system that will capture a 1000 cm^2 circular area onto the 0.25 cm diameter faceplate of the image intensifier and, naturally, with as little distortion as possible. The requirements are outlined in table 3. We have settled on a Cooke triplet lens configuration as the best solution. The system has been fabricated and will be ready to be tested with the Kodak XHF camera later this fall.

Table 3. Summary of key requirements of polarimeter optics.
UV grade optics - must have high transmission at 290 nm wavelength
Demagnification factor of 1/14.29
RMS spot size ~ 25μm (corresponds to CCD pixel size after further demagnification by fiberoptic taper)
Compact and rugged design for a balloon-borne experiment.

C. Performance Predictions

Monte Carlo calculations anchored to the experimentally determined modulation factor of 0.3 at 54 keV provide us with predictions of the minimum polarization that will be detectable by XIMP. Figure 8 shows the results of such a calculation for the Crab Nebula. The results for minimum detectable polarization are given in three energy bands: 30 keV - 40 keV, 40 keV - 50 keV, and 50 keV - 60 keV. Within each energy band, the calculation has been performed for a 10,000 second observation - a typical single observation duration for a balloon flight and for a 30,000 second observation, if conditions are favorable enough to allow a three day flight. If we could fly three such detectors on a long duration flight, from Antarctica for example, much higher sensitivities would be realized and we could conceive, among the many new possibilities, of performing x-ray polarimetry on the Crab pulsar and looking at how polarization varies as a function of pulse phase.

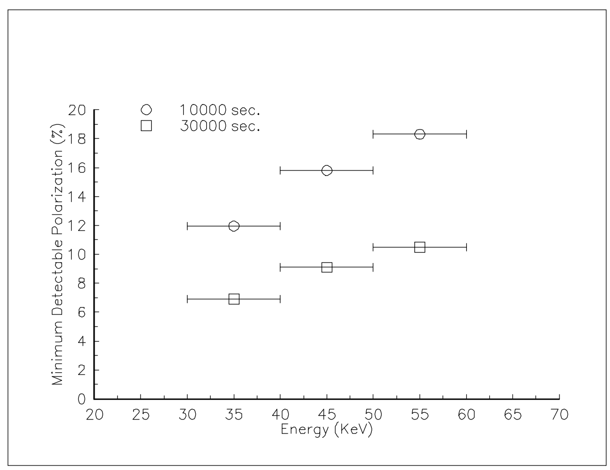

Figure 8. Minimum detectable polarization values expected during observations of the Crab Nebula by the MSFC hard x-ray imaging polarimeter.

D. Current Status Of Work

Much of the essential electronic hardware for XIMP has been procured or built. Fabrication of the optical system is nearly complete and delivery from the vendor is expected imminently. The pressure vessel is currently being built in the MSFC shops and will be delivered shortly. Other aspects of the optical avalanche chamber (i.e. grids, field shaping rings, placement of high voltage feedthroughs, etc.) are under design or study. Also the interface between XIMP and its balloon gondola - to allow rotation about XIMP's optical axis - is being designed. As XIMP will have a dedicated gondola (also being designed and built at MSFC), flight of the XIMP is contingent upon the gondola's completion.

Once we receive the XIMP optics, we will be ready to once again modify the protoype XIMP. With the exception of the optical avalanche chamber, this final prototype will fully utilize flight hardware and will replicate the flight XIMP in every important way. We will use this prototype to further optimize the XIMP design and continue to explore XIMP's capabilities.

V. SUMMARY

We have summarized the capabilities and presented a status report of XIMP, an x-ray imaging polarimeter being designed, developed and built at NASA's Marshall Space Flight Center. XIMP's ability to simultaneously combine imaging with polarization analysis is, to our knowledge, matched only by the pixel polarimetry scheme mentioned in the introduction. As assessed in a paper by Holland et al, the pixel polarimeter shows great promise in the area of x-ray astronomy[6]. However, XIMP has some clear advantages over the pixel polarimeter. For the pixel polarimeter, x-rays are absorbed directly in the silicon of the CCD. Though modulation factors as high as 34% are predicted at 40 keV for x-ray optimized CCDs having 4μm pixels, the absorption efficiency of a silicon-based CCD is vanishingly low at these energies. Also without an optical system to increase the effective area of their polarimeter, the cost and electronic complexity of covering large areas would be prohibitive. Hence progress is contingent upon the development of multilayor optical systems, or some other technique to increase the effective area of the pixel polarimeter. Since XIMP relies on an optical avalanche chamber to facilitate imaging of photoelectron tracks by a CCD camera, a XIMP-type polarimeter can be scaled up in size with only moderate increase in cost and complexity.

VI. REFERENCES

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