DEVELOPMENT OF A HARD X-RAY IMAGING POLARIMETER

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ABSTRACT

An optical imaging chamber can be used to detect x-rays by imaging the tracks of photoelectrons ejected when the x-rays are absorbed in the detector volume. These tracks contain information about the location of the x-ray interaction point and its polarization. In the lab, we have obtained a modulation factor of 30% for 60 keV polarized x-rays. Here we discuss preliminary work done towards building a large area hard x-ray imaging polarimeter which will be able to measure x-ray polarizations from bright cosmic x-ray sources at energies between 40 keV and 100 keV.

1. INTRODUCTION

The astrophysical applications of x-ray polarimetry have been discussed many times in the literature[1]. X-ray polarization is expected to arise from non-thermal emission (i.e., synchrotron radiation), scattering of x-rays in accretion disks and their coronae; and the emission and propagation of x-rays in the extremely strong magnetic fields characteristic of neutron star sources such as rotation and accretion powered pulsars. Supernova remnants, binary x-ray sources powered by accretion disks, black hole candidates, and active galactic nuclei are among the cosmic x-ray sources which are expected to emit polarized x-rays.

Polarization measurements can put added constraints on models which qualitatively reproduce pulse profiles. For a rotation powered pulsar such as the Crab pulsar, the comparison between optical and x-ray polarization could determine if x-ray and optical pulses arise from a common source such as synchrotron emission or if multiple mechanisms need be considered. For accretion-powered pulsars such as Her X-1, the strong energy dependence of the amplitude and position angle of the polarization vector near the cyclotron resonance line (35 keV)[2], would permit studies of material trapped inside the magnetosphere which happen to pass through the line of sight.

Up to the present, only one definitive measurement of polarized x-rays from a celestial source has been made: the OSO-8 measurement of 19 % linear polarization from the Crab Nebula at 2.6 keV and 5.2 keV[3]. The lack of additional positive measurements of x-ray polarization is due to the inherent inefficiency of the polarimeters flown on OSO-8[4] and Ariel V[5] in the mid 1970's

We are currently developing a device which will utilize the novel technique of optical imaging[6] to measure both the absorption location and polarization direction of incident x-rays. Planned to be flown as part of a high-altitude balloon payload, the x-ray imaging polarimeter will make polarization measurements of the Crab Nebula and pulsar, Cyg X-1, and Her X-1 at energies above 30 keV. This device will complement the Stellar X-Ray Polarimeter (SXRP)[7] which will make polarization measurements at energies below 20 keV from aboard the Russian Spectrum-X-Gamma mission.

2. PRINCIPLE OF OPERATION

This polarimeter will utilize the optical imaging technique described in detail elsewhere[5] to determine polarization of incident x-rays by imaging photoelectrons and utilizing the correlation between polarization of the incident beam and the ejection direction of photoelectrons. Briefly, the optical imaging technique is based upon the use of a parallel plate proportional counter

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filled with a noble gas (argon in this particular case) and an added quench gas, trimethylamine (TMA, $(CH_4)_3$ N), which also acts as a photosensitive vapor that converts argon excitation energy into large quantities of photons with wavelengths peaking at 290 nm in the near UV (refer to figure 1). When the detector is operated at overall electron gains in excess of 1000, the total number of photons emitted is sufficiently large to permit imaging by a CCD camera having only one stage of intensification.

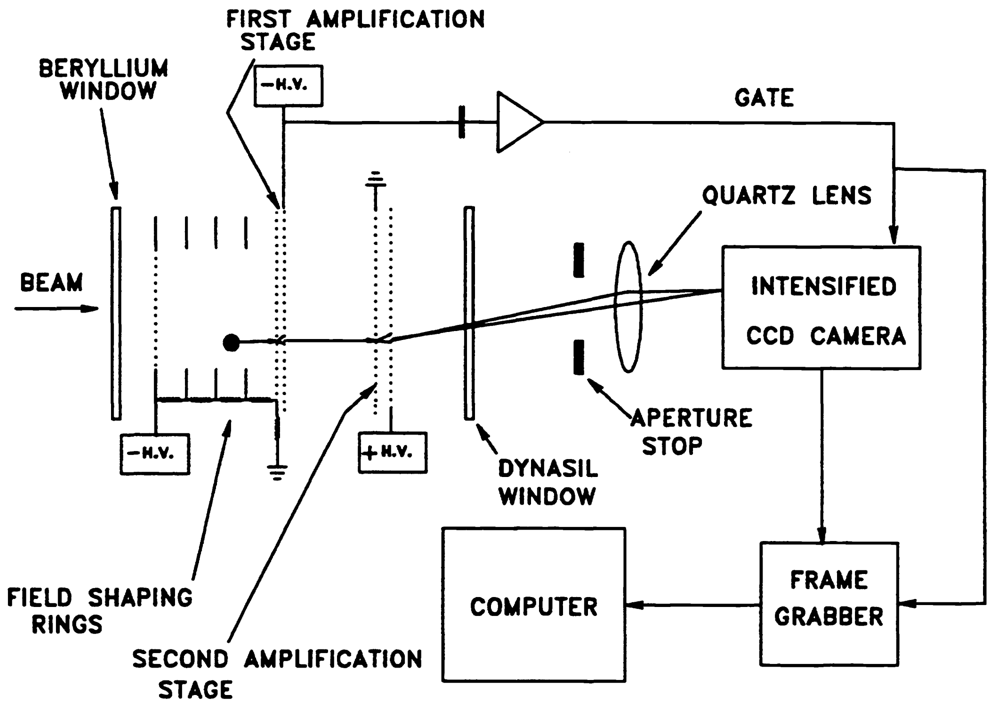

Figure 1. A schematic view of the optical imaging detector used in our laboratory.

A critical parameter for evaluating the sensitivity of any polarimeter is the modulation factor. This number is obtained by dividing the amplitude of a sine curve fitted to the angular distribution of photoelectrons by the constant offset of that sine curve (after background subtraction) from zero. So far, we have measured a modulation factor of 0.3 for 60 keV x-rays incident upon the detector (see figure 2). The magnitude of the modulation factor depends upon how accurately the ejection direction of a photoelectron can be measured. As x-ray energies decrease, photoelectrons have shorter tracks in the optical imaging chamber, and it becomes more difficult to measure the ejection direction, and hence, the modulation factor will decrease at lower energies. Monte Carlo studies indicate that this technique cannot be used to measure polarization for x-rays having energies much below 40 keV. To determine the modulation factor at lower energies, we have obtained a ^{157}Gd to provide x-ray lines between 40 keV and 50 keV, and these measurements will be made within the year.

To obtain the largest possible modulation factor, the ejection direction of each photoelectron must be measured very near to the start of its track since the photoelectrons experience many collisions before they come to rest, and information about their ejection direction is quickly lost. A fundamental physical limitation on our ability to measure the ejection direction is diffusion of the cloud of secondary electrons as it is drifted through the detector volume. In one centimeter of drift, the RMS spread of electrons due to diffusion is typically on the order of a few hundred microns. In practice, the direction of the photoelectron has to be measured over a distance of less that 4 mm to obtain a modulation factor of 0.3. Clearly the diffusion must be significantly less than 4 mm to obtain a good polarization measurement.

The optical imaging chamber lends itself nicely to measurements of gaseous diffusion. Figure 3 shows a series of diffusion measurements obtained by measuring the spread of tracks formed by the absorption of 5.9 keV x-rays from ^{55}Fe; the photoelectron tracks ejected by absorption of these x-rays are very short (< 0.2 mm at 1 atm) and their spatial extent is dominated by diffusion.

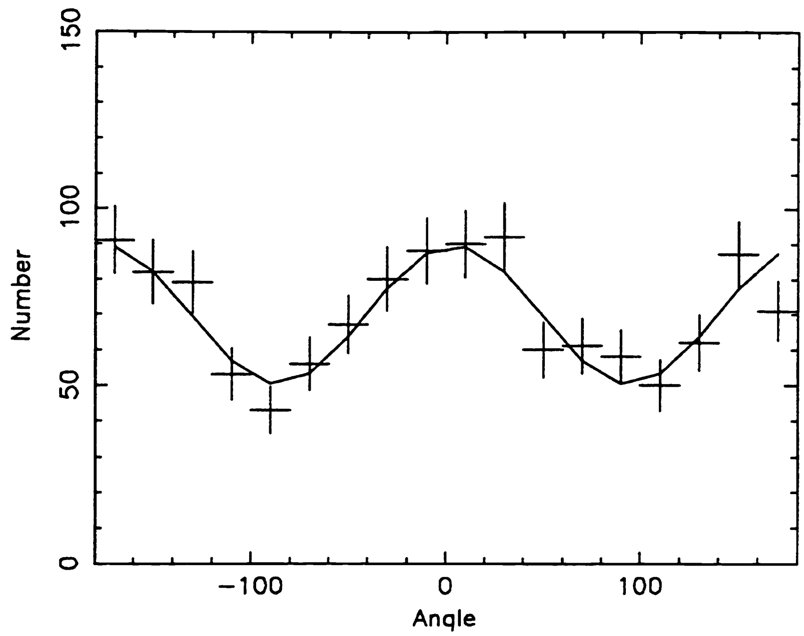

Figure 2. Distribution of photoelectron ejection angles measured in the optical imaging chamber. These data were taken by shining highly polarized (92 %) 60 keV x-rays onto the detector. The ratio of the amplitude of the fitted sine curve to the average number of events per bin (modulation factor) is 0.3 for this distribution.

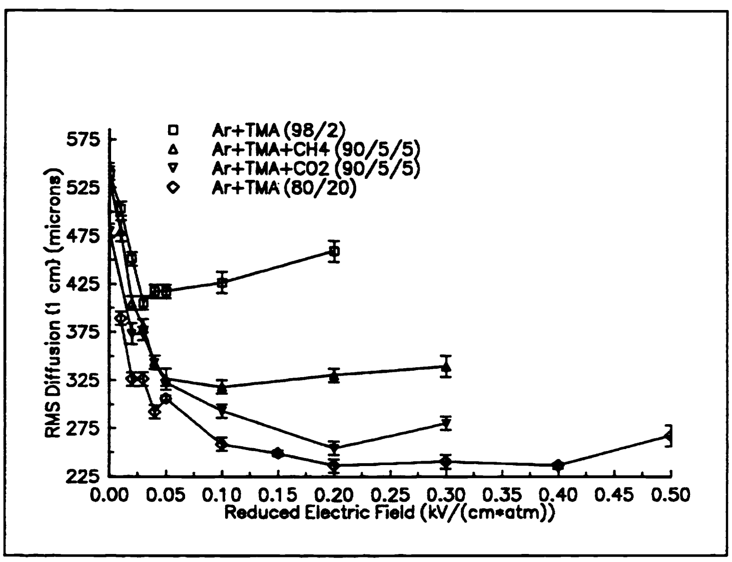

Figure 3. Diffusion measurements obtained for a variety of gas mixtures using the optical imaging chamber. The plotted numbers are the RMS spread of the electron cloud after drifting a distance of 1 cm.

The Ar+TMA (90/10) mixture used in our measurements of polarization had a measured RMS spread due to diffusion of 300 microns (after 1 cm of drift) for a reduced electric field of 0.2 kV/cm-atm. From figure 3, a mixture containing Ar+TMA+CO_2 (90/5/5) would have lower diffusion without increasing the fraction of the mixture comprised of quench gases. This and mixtures containing an even higher CO_2 to TMA ratio will be explored in the future. In the case of xenon, the light yield saturates for small quantities of added TMA and nothing is gained by adding more than 1% TMA to the mixture[8]. The level of

TMA required to reach saturation must be measured still, but there is no reason to suppose that mixtures such as Ar+TMA $+CO_2$ (90/1/9) cannot provide satisfactory light yields and even lower diffusion values. Because of the poor absorption efficiency of argon at the energies the polarimeter will have to work at, a large absorption depth of the order of 50 cm will be needed. Since the RMS spread of the cloud grows as the square root of the drift distance, it is critically important to keep the diffusion as low as possible for maximum sensitivity.

3. THE HARD X-RAY IMAGING POLARIMETER

Figure 4 shows a schematic layout for the polarimeter. The optical avalanche chamber at the front of the polarimeter will have two stages of amplification. The first stage will be used to provide a trigger pulse to the camera; this reduces image noise by exposing the camera to light only when there is an event in the chamber. The sensitive area of the optical avalanche chamber will be 1000 cm^2, and the absorption depth will be 50 cm. The chamber will be filled with a low diffusion mixture of argon and TMA and possibly CO_2 at a pressure of two atmospheres. As can be seen from figure 3, the low diffusion mixtures work best at high drift fields, and voltages in excess of 10 kV will have to be applied across the drift region.

The light emitted from the optical avalanche chamber will be focused by UV grade optics onto an intensified CCD camera. The light cone from the chamber will be diverted by two diagonal mirrors to keep the detector as compact as possible. A camera currently being considered for this project (Kodak KAI-1001) has a resolution of 1008 (H) by 1019 (V) pixels. To fully utilize the CCD, dual outputs for even and odd video fields make possible non-interlaced operation at 30 frames per second. The pixels are square having a dimension of 9 μm on a side. Images will be digitized by two high-speed VME bus frame grabbers and stored on 8 mm tape (see figure 5). In flight, the entire unit will be rotated about its optical axis at a rate of approximately 1 RPM to average out any nonuniformities in detector sensitivity which could systematically bias the polarization measurements.

To image a 1000 cm^2 detector area on a single CCD chip would mean an overall reduction of resolution, in terms of pixels per unit object length, by a factor of 5 (see figure 6.) over that used in our laboratory. The expected resolution would still be a factor of about eight better than the spreading of the electron cloud by diffusion in the absorption region of the polarimeter, so we expect no significant degradation in sensitivity from the decreased resolution.

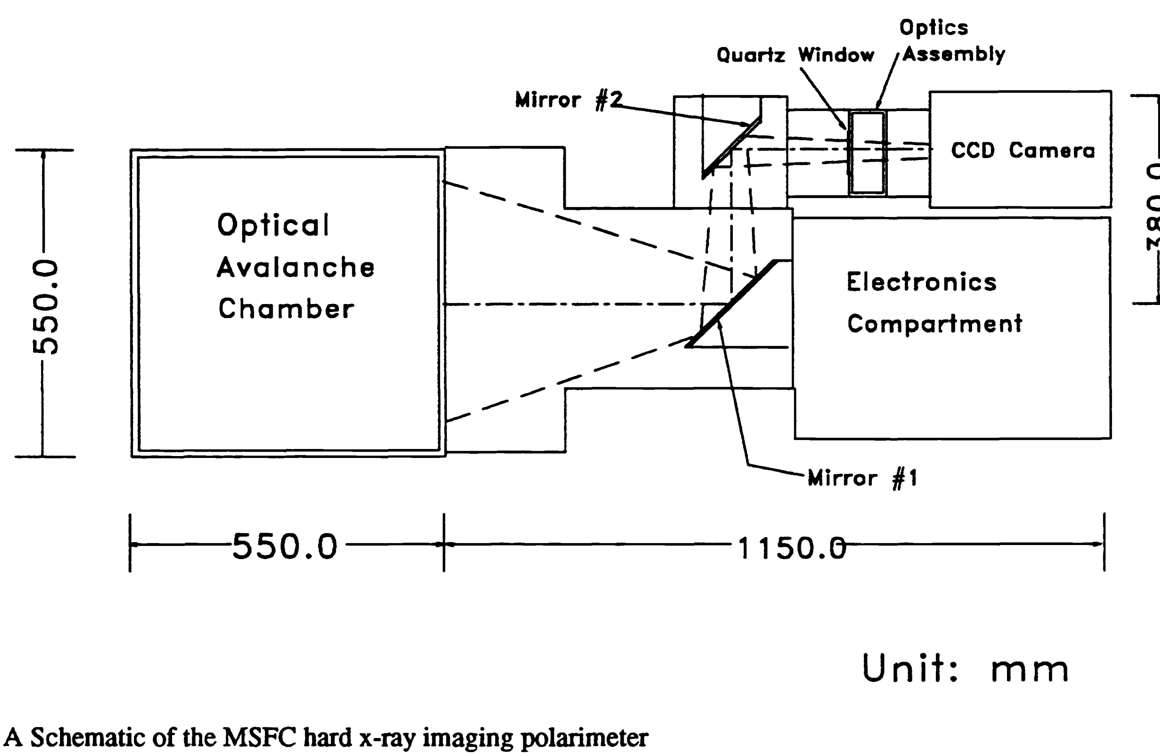

Figure 4. A Schematic of the MSFC hard x-ray imaging polarimeter

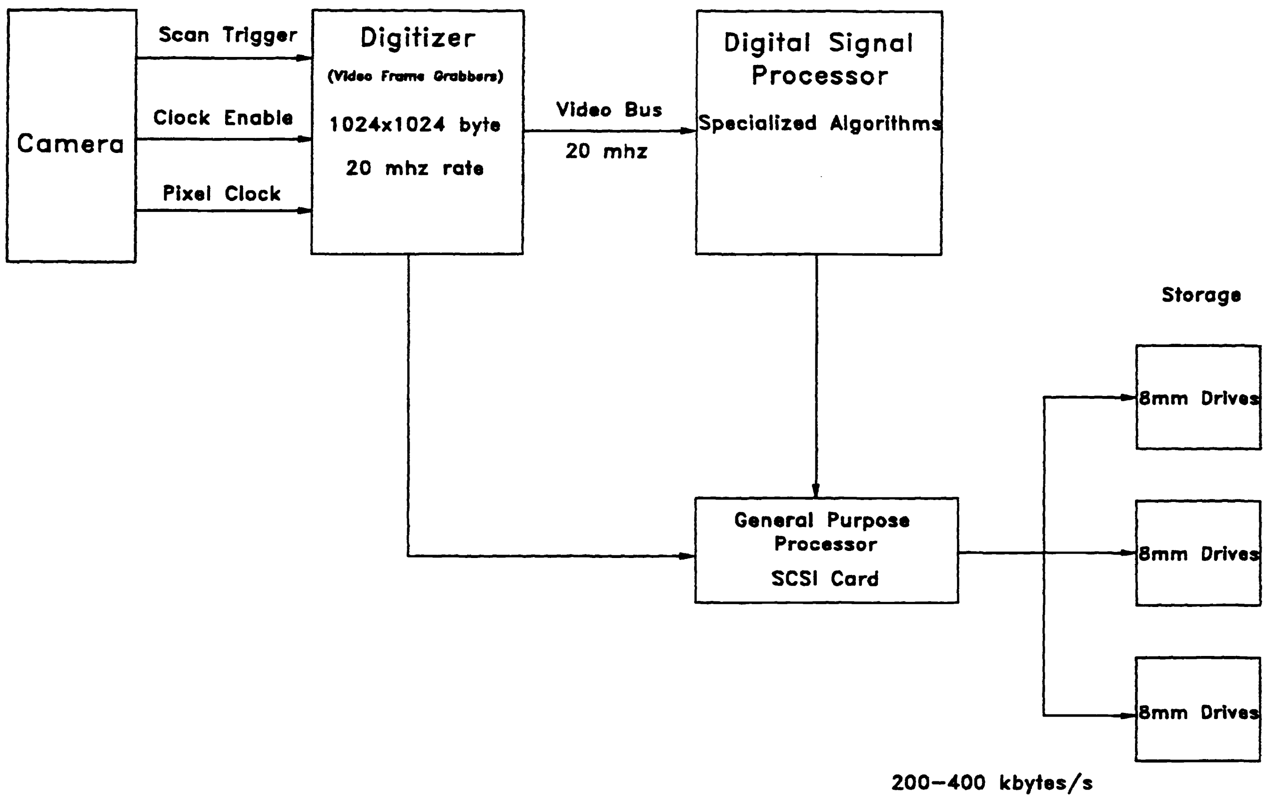

Figure 5. A schematic of the planned polarimeter electronics

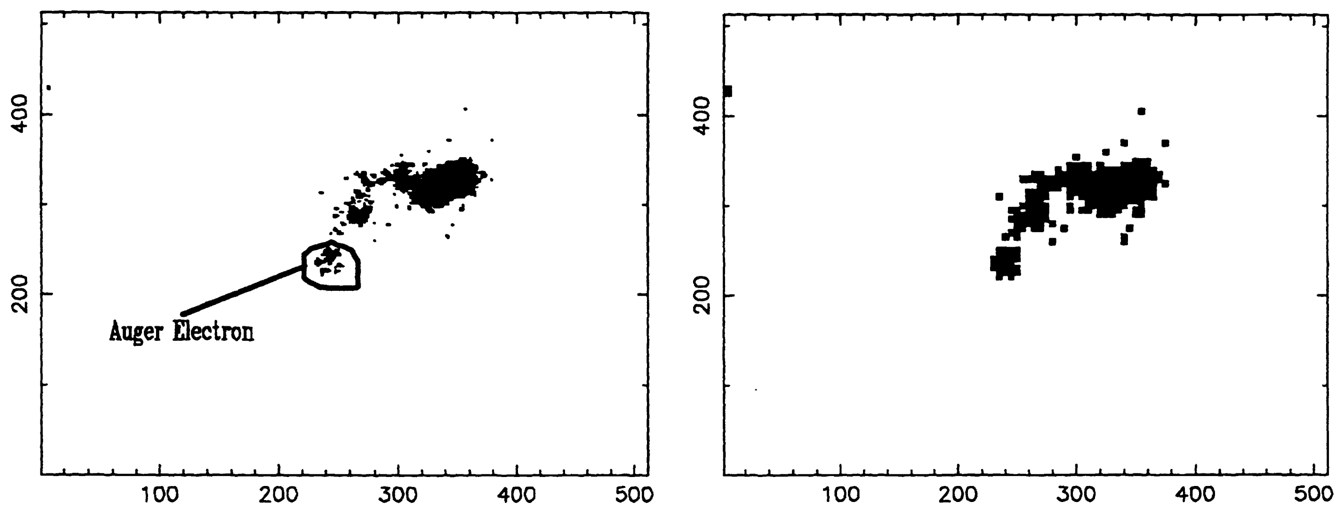

Figure 6. The figure at left contains the image of an actual photoelectron track as it appears in the optical imaging chamber used for this work; the location of the Auger electron is indicated. The figure on the right shows how the same photoelectron track would appear in the polarimeter.

4. DATA ANALYSIS

The frame rate of the camera is similar to the event rate expected from the prime targets for this polarimeter, so many frames will contain multiple events, and data analysis will be complicated by the necessity of knowing the time of arrival of each event to a precision better than the 33 ms camera integration time. The charge signal produced by the optical avalanche chamber can be used to assign a time to an event. Having an energy resolution (FWHM) of 0.13 at 22 keV and a duration of the order of 1 μs, the charge signal can be used to assign an accurate time of arrival to each event in the frame; since energy and image brightness are correlated, energies and times can be mapped uniquely to events in the frame providing the image field is not too crowded..

In principle, better than 99 % of the charged particle background can be rejected with almost no loss of bona fide x-ray events. This high efficiency is due to the large probability that minimum ionizing particles will produce tracks in the chamber which are very long compared to the tracks made by photoelectrons having energies between 30 keV and 100 keV. At present, we plan to store all events detected in the chamber and implement background rejection in software. In the future, the addition of more sophisticated electronics will make real time charged particle rejection a possibility.

If used with a coded aperture mask, the polarimeter will be able to image sources of polarized x-rays. To be able to image effectively, events must be accurately located in x and y. The highly convoluted electron tracks are difficult to analyze, but nature provides a simple means of fixing the event location. In argon, 80 % of photoelectric absorptions result in the emission of a 3 keV Auger electron at the interaction point (see figure 6). These low energy electrons come to a stop in a distance short compared to the size of the diffused electron cloud, and if utilized effectively, the Auger electron can be used to achieve good spatial resolution (< 1 mm RMS) even for tracks several centimeters in length.

5. SENSITIVITY

The sensitivity from polarization measurements is calculated from the formula[9]:

$$MDP = (429/\mu R)((R+B)/T)^{0.5}, \tag{1}$$

where MDP is the minimum detectable polarization (%) at the 99 % confidence level, μ is the modulation factor (0.3 is assumed here), T the integration time, and S and B are the source and background count rates, respectively. Figure 7 shows the results of our sensitivity calculations for the Crab Nebula. These calculations assumed a standard balloon float altitude corresponding to 3 gm/cm^2 residual atmosphere, and it is assumed that the source is at a zenith angle of 30^o. The background spectra used are assumed to be flat over the energy band in which the polarimeter is sensitive: a constant 2×10^{-4} photons/cm^2-sec-keV has been used. This number represents the projected residual instrument background with moderate shielding and efficient charged particle rejection; a careful choice of detector body materials may reduce this flux further[10]. One can see from the figure that the 19 % polarization of the Crab, if it persists in these bands, can be measured in under three hours of observation - a reasonable observation time for a balloon flight. Cyg X-1 has a slightly harder spectrum than the Crab, but is also variable and should give the same polarization sensitivity as the Crab.

If several polarimeters are flown together on a long duration balloon flight, two other interesting sources, Cyg X-3 and Her X-1, become accessible to polarization measurements. The Crab pulsar, having one tenth the flux of its surrounding nebula will also be accessible and correlations between polarization and pulse phase could be investigated. Table 1, below, gives the predicted MDP values for several sources assuming a 9000 cm^2 total detecting area and a 10^5 sec on source observation time.

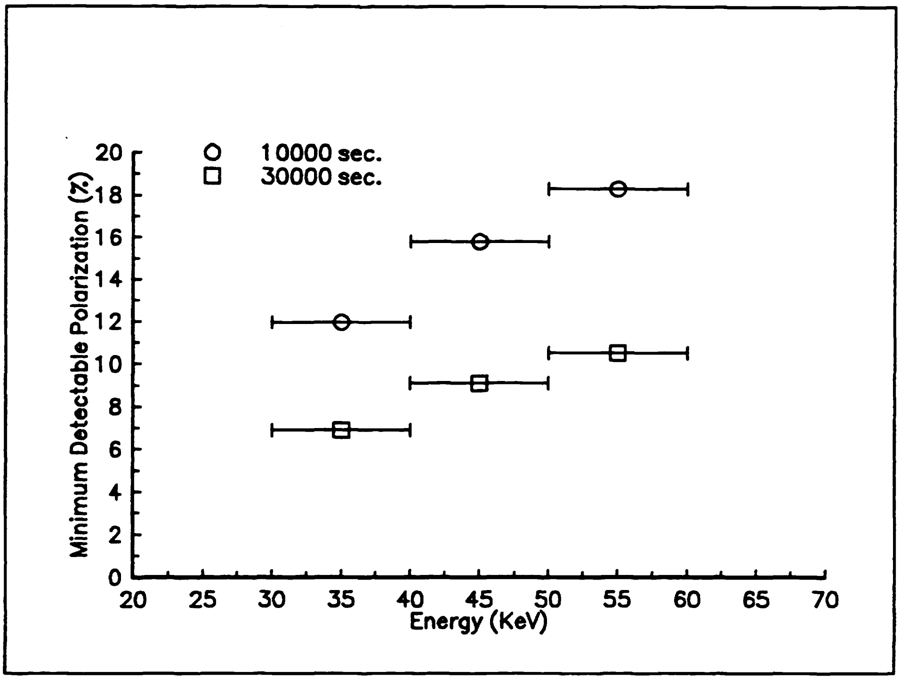

Figure 7. Values for the minimum detectable polarization from the Crab Nebula for two different observation times.

Table 1. X-RAY POLARIMETER SENSITIVITIES FOR LARGE AREAS AND LONG OBSERVATION TIMES (10^5 sec) Argon filled detectors, 2 atm, 9×10^3 cm^2, 50 cm deep absorption region.

MDP (%) for 10^5 sec observation					
Band keV	Crab Nebula	Crab Pulsar Primary Pulse	Cyg X-1	Cyg X-3	Her X-1
30-40	1.3	29.8	1.3	10.0	7.5
40-50	1.7	38.7	1.6	19.0	19.4
50-60	1.9	43.8	1.7	10.0	7.5
optimum band	**(30-60) 0.9**	**(30-50) 23.9**	**(30-60) 0.8**	**(30-40) 10.0**	**(30-40) 7.5**

6. SCHEDULE

During the remainder of 1993, we will investigate low diffusion gas mixtures in a detector having a large absorption depth (50 cm) to determine if a modulation factor of 0.3 at 60 keV can be maintained or improved upon. We will also measure the polarization at lower energies to see what modulation factors are achievable below 60 keV. As is evident from this paper, some thought has already gone into the overall polarimeter design, so we plan to order the CCD camera and some of the electronics toward the end of this year. During 1994, we hope to assemble all the necessary data acquisition hardware: camera, frame grabbers, etc. to begin testing the system in the laboratory. In addition, we will finalize the polarimeter design and begin machining the polarimeter body before the year is out. During 1995 we will assemble the complete detector system and attempt a high altitude balloon flight during the fall campaign to observe the Crab and Cyg X-1.

7. CONCLUSION

A hard x-ray imaging polarimeter utilizing optical imaging is currently under development. The successful application of the optical imaging method to measure the polarization of hard x-rays has been demonstrated in the laboratory. Measurements of gaseous diffusion in the optical imaging chamber have lead to lower diffusion gas mixtures which should result in improved sensitivity. We have presented a preliminary design for a polarimeter for balloon borne astronomy and discussed how data from the polarimeter will be handled. Finally, we have presented the predicted sensitivities for the Crab during a normal balloon flight as well as sensitivities for several strong hard x-ray sources in the event that a long duration flight of several polarimeters is possible.

8. ACKNOWLEDGMENTS

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