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Large-Area Balloon-Borne Polarized Gamma Ray Observer (PoGO)

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Abstract— **We are developing a new balloon-borne instrument (PoGO), to measure polarization of soft gamma rays (25-200 keV) using asymmetry in azimuth angle distribution of Compton scattering. PoGO will detect 10% polarization in 100mCrab sources in a 6-8 hour observation and bring a new dimension to studies on gamma ray emission/transportation mechanism in pulsars, AGNs, black hole binaries, and neutron star surface. The concept is an adaptation to polarization measurements of well-type phoswich counter technology used in balloon-borne experiments (Welcome-1) and AstroE2 Hard X-ray Detector. PoGO consists of close-packed array of 397 hexagonal well-type phoswich counters. Each unit is composed of a long thin tube (well) of slow plastic scintillator, a solid rod of fast plastic scintillator, and a short BGO at the base. A photomultiplier coupled to the end of the BGO detects light from all 3 scintillators.**

The rods with decay times < 10 ns, are used as the active elements; while the wells and BGOs, with decay times ~ 250 ns are used as active anti-coincidence. The fast and slow signals are separated out electronically.

When gamma rays entering the field-of-view (fwhm$\sim$ 3deg^2) strike a fast scintillator, some are Compton scattered. A fraction of the scattered photons are absorbed in another rod (or undergo a second scatter). A valid evnet requires one clean fast signal of pulse-height compatible with photo-absorption ($>$ 20keV) and one or more compatible with Compton scattering ($<$ 10keV). Studies based on EGS4 (with polarization features) and Geant4 predict excellent background rejection and high sensitivity.

I. INTRODUCTION

In the X-ray observation of extra-solar system, polarization has been measured only once, by an exploratory and yet very successful experiment, of the Crab (nebula+pulsar) at 2.6 and 5.2keV with OSO-8 Satellite [1]. Since then, polarization measurement has been known to play crucial roles in high energy astrophysics. The most interesting and challenging measurements are those sensitive to polarization at the 10% level within characteristic time-scales of prominent flares and transients (lasting less than a day) for flux level of $50 - 100$mCrab.

Two detector technologies are now being developed to reach the required sensitivity. The first technology, effective below 10keV, is based on tracking of the photoelectron from X-ray absorption in a micron-scale gaseous imaging device (eg. [2]). The other, effective between a few tens of keV to a few MeV, is based on the coincidence measurement of Compton scattering and photo-absorption (eg. [3]). The direction of photoelectrons in the first, and that of the scattered gamma rays in the second, depend on the photon polarization. There are three figures of merit for polarization measurements. One is the modulation factor, the azimuth angle response of the instrument for a 100% polarized source. The second is the signal to background ratio: in real observation, instrumental background and source confusion will dilute the modulation factor significantly. The third figure of merit is the effective area usable for polarization measurement. These three figures of merit are often coupled: the effective area may have to be sacrificed to gain in the modulation factor and to improve signal to background ratio.

The two technologies will make high sensitivity polarization measurement possible in many X-ray and gamma ray astronomical objects and add a new page to the study of Active Galactic Nuclei, Galactic X-ray binaries with compact stars, inverse Compton dominated objects, synchrotron radiation sources including that from the sun.

We propose here a novel instrument based on the Compton scattering technology: it is optimized in the hard X-ray band (25-200 keV) and aims to resolve several key physics issues via polarization measurements in a series of balloon experiments lasting ∼6-8 hours each. Compton scattering has highest potential for measuring low polarization because its modulation factor exceeds 85% for a large solid angle between 60-120 degrees. The other choice, the photoelectron tracking, operates in the soft X-ray band and hence the instrument has to be launched to a satellite orbit. It has, however, the important advantage that a fine image can be obtained by combining with a high throughput X-ray mirror.

Science and instrumentation related to the polarization mea-

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TABLE I

BASIC PERFORMANCE OF POGO (CURRENT DESIGN)

Parameter	Value
Energy band	25-200 keV
Geometric area	1787 cm^2
Modulation factor	23%
Effective area for pol measurement	274 cm^2
Sensitivity to pol. (1σ) in a 6-hour obs. of a 100 mCrab source	2.2%

surement of astronomical objects in the X-ray and hard X-ray bands have been reviewed in articles by Lei et al. [4] and by Dean [5].

The proposed instrument, named Polarized Gamma Ray Observer (PoGO), is based on the Well-type Phoswich Counter design [6] [7]. The design has been tested in several balloon experiments and proven to be highly effective in reducing background [8]. Subsequently, the technology has been adopted in the AstroE/AstroE2 satellite mission as the Hard X-ray Detector [9] [10]. The design presented here consists of 397 well-type Phoswich Detector Cells (PDCs) made of fast and slow scintillators, and a set of anti-coincidence counters (Side Anti-Coincidence Shield) made of BGO. The 397 PDCs function collectively as an active collimator, an active shield, and a Compton polarimeter. A signal-to-background ratio of greater than 10 is expected for a 100 mCrab source between 25 and 100keV. For a geometrical area of $\sim$ 1787 cm^2, the proposed instrument will detect $\sim$ 6.6% polarization of a 100mCrab source at 3σ in one 6-hour balloon observation (Table 1).

In the following we describe the instrument design, the relevant parameters, the expected performance based on test results and computer simulations. We also discuss the design with respect to PoGO's science goals, in particular, polarization measurements on a rotationally powered pulsar, Crab Pulsar and an accreting Galactic black hole, Cygnus X-1.

II. DESIGN OF THE INSTRUMENT

Rquirements crucial to measuring 10% polarization of a 50-100 mCrab object in a 6-hour balloon flight are listed below. These are determined through Monte Carlo simulation studies described later.

- Sensitive energy range must extend below $\sim$40-50 keV to gain photon counts.
- Compton scattering events with a scattering angle between $\sim60°$ and $\sim120°$ must be selected by coincidence method to ensure a reasonable modulation factor.
- Background event rate must be reduced to $\sim$10 mCrab equivalent.

These requirements have led to the conceptual design based on the Well-type Phoswich Counter technology [6] [7] (Fig.1). As will be elaborated later, Monte Carlos studies indicate that the hexagonal well of the PDC must be long (see Fig.2), tightly bundled together (Figs.1 and 3), and surrounded by the Side Anti-Coincidence Shield (SAS) (Fig.1 and caption of Fig.3).

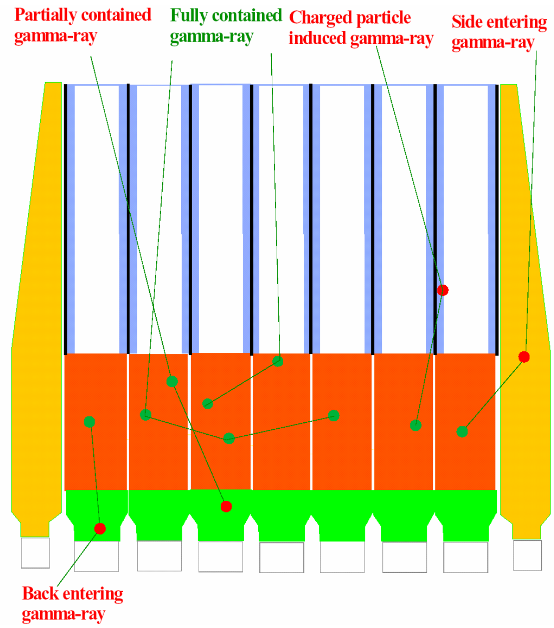

Fig. 1. Conceptual design of PoGO: It consists of an array of well-type Phoswich Detector Cells (PDCs), each made of a fast plastic scintillator rod (the rectangular part in the middle), a slow palstic scintillator hexagonal tube (the parallel stripes), a thin high-Z metal foil (the line between the neighboring stripes), and a BGO base (the tapered area at the bottom). A set of Side Anti-Coincidence Shield (SDS) made of BGO surrounds the array of PDCs. Scintillation light from one PDC is read out by a photo-multiplier tube (the small rectangular box) attached to the bottom BGO. Superimposed in the figure are representative passages of gamma rays and cosmic rays with energy deposition marked by circles: the trigger scheme described in the text are designed to accept the ones marked as "Fully contained gamma-ray".

The PDC produces light pulses with a fast decay time ($\sim$2 nsec) from the fast plastic scintillator rods, and/or, with a slow decay time ($\sim$200-300 nsec) from the well scintillators and/or BGO. To select the valid event type labeld as "Fully contained gamma ray" in Fig.1, the trigger electronics must sense a PDC with an appropriate signal in the fast scintillator, but no detectable energy in the slow well scintillator nor in the BGO anticoincidence. Subsequently, remaining PDCs must be examined to assure full containment of the gamma ray.

In a stand-alone phoswich detector, the valid signal can be filtered by a Pulse Shape Discrimination (PSD) circuit. When a large number of phoswich detector units have to work collectively like in AstroE-HXD [9] [10] and PoGO, the filtering is more efficiently done with a hierarchical trigger. A simplified block diagram of the proposed electronics design is given in Fig.4.

In the design, the hierarchial trigger and PSD are combined into three switched integrators: this allows the electronic systems to be simplified, power-efficient, and cost-effective. The readout electronics shown in Fig.4 detects the photo-absorption of a gamma ray in the energy range of PoGO, effectively suppresses background at one PDC level, and initiates readout of the full detector array.

Each PMT has two outputs, one from the anode and the other from the last dynode (Fig.4). The anode signal is applied to a

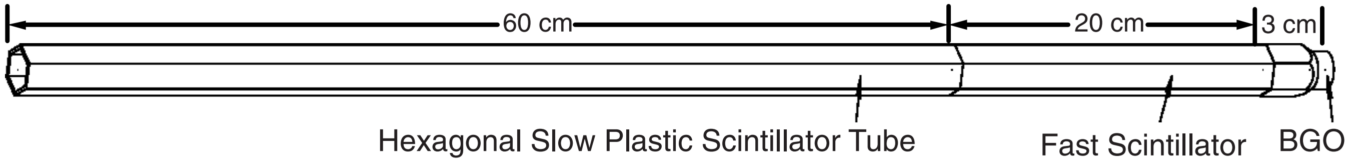

Fig. 2. One well-type Phoswich Detector Cell (PDC) consiting of a 60cm long active anti-coincidence well made of slow plastic scintillator (decay time: ∼200-300 ns), a 20 cm long detection part made of fast plastic scintillator (decay time: a few ns), and a 3-5 cm long BGO. All scintillators are optically coupled and read out by one PMT.

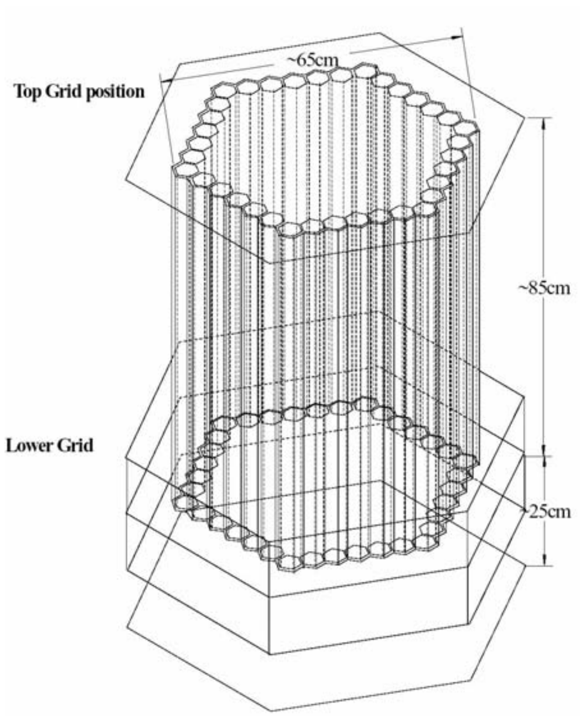

Fig. 3. The 397 well-type Phoswich Detector Cells (PDCs) are tightly bundled and surrounded by the Side Anti-coincidence Scintillators (SDS) to reduce the cosmic ray induced background event rate. Note that only a outer-most PDCs are shown here. The SDS (not shown) wraps around the outer-most PDCs to about two thirds of the PDC in height (∼85 cm).

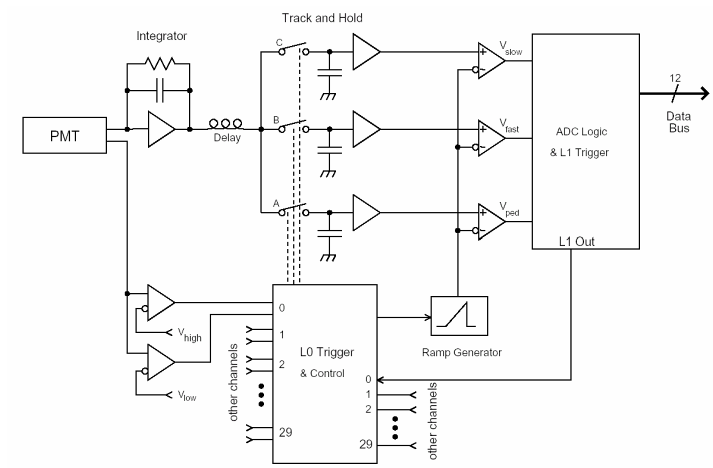

Fig. 4. Block diagram of readout electronics: Each PMT of PDC is read out from the anode and the last dynode. The anode signal goes directly to two comparators and L0 Trigger and Control. If L0 is met, the dynode signal waveform of the PDC is sampled at 3 timing to extract the pedestal, the integrated yield of the fast scintillation component, and that of the slow scintillation component. These sampled pulse heights are processed by ADC Logic and L1 Trigger. When L1 is met, the whole PDC array and SAS will be read out.

pair of comparators that act as a fast single channel analyzer. Its lower threshold is set to the minimum signal expected from the photo-absorption of a ∼19 keV gamma ray: Note that as shown in Fig.5, the final energy of Compton scattered gamma ray exceeds 22 keV in the energy range of PoGO. Its upper threshold is set well below the signal expected from the passage of a charged cosmic ray. The dynode signal is integrated and the output of the integrator is coupled through a delay line to three track-and-hold circuits. They are read out by dual-rate Wilkinson rundown circuits that have both trigger and analog-to-digital converter functions.

A pulse within the single channel analyzer window of any PDC generates a Level-0 (L0) trigger that starts the hold sequence for the track-and-hold circuits for the whole array. The circuits samples the integrator baseline at a time before the arrival of the signal to provide a pedestal measurement,

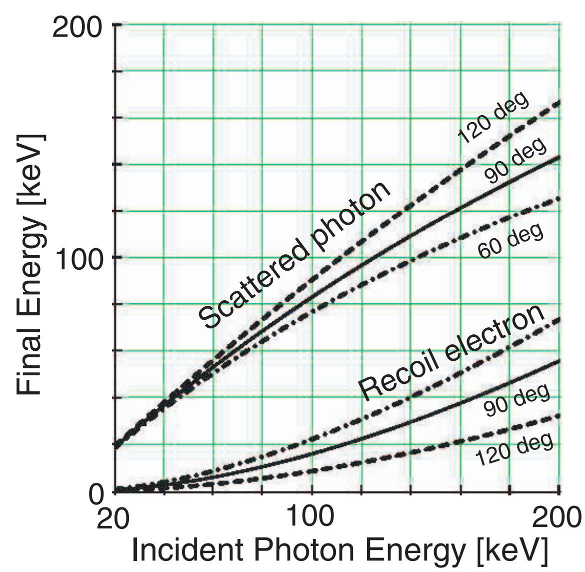

Fig. 5. Compton kinematics in the PoGO energy range. Note that the energy deposition is separated for the scattered photon (photo-absorption site) and the recoil electron (Compton scattering site) in the PoGO energy range (25-80 keV).

then at a time corresponding to about 10 ns after the arrival of the PMT signal to measure a fully integrated fast scintillator signal, and finally at about 1 μs to sample a fully integrated slow signal.

After all three pulse heights are sampled, the Wilkinson circuits on the hit PDC runs with a fast ramp to quickly digitize the held voltages with moderate (6-bit) precision. Then the pedestal-subtracted fast and slow signals are compared to filter out background events and generate Level-1 (L1) trigger. For the filtered events the whole PDC array as well as the Side Anti-conicidence Shield are read out with 12-bit precision. A software cut is applied to reject events in which one or more PDC have significant slow component, or in which SAS is hit.

Events will be time-tagged using times derived from the GPS so that the phase dependence of polarization from pulsars can be examined.

III. Monte Carlo Simulation and Design Optimization

The current design parameters of PoGO given in Tables 1 and 2 are the results of optimization obtained after extensive computer simulations. We used EGS4 [11] and Geant4 [12] to study the instrument response to polarized gamma rays and background cosmic rays. The version of EGS4 used in this study has the Compton scattering cross-section not averaged over the inital photon polarization states nor summed over the final photon polarization states [13]. Hence the gamma ray polarization is fully followed in multiple steps of Compton scatterings. The program has been validated to about a few % level by comparing with polarization measurements [14]. Geant4, on the other hand, has not been implemented fully with the polarization dependent Compton cross-section. It facilitates, however, simulation of complex detector geometry. Hence we used EGS4 to study polarization dependent performances and Geant4 to estimate background rates by cosmic rays.

The cosmic ray model used in this study has been developed largely based on the observation made by GLAST Balloon Flight Engineering Model (BFEM) at Palestine Texas [15]. The GLAST-BFEM consists of 13 pairs of x- and y-sampling single-sided silicon strip detector layers, each covering approximately 30 cm×30 cm in area. The 13 pairs of layers are intersparsed with thin lead converters ($\sim$3% X_0 each) and followed by an imaging electro-magnetic calorimeter made of 96 CsI(Tl) logs [16]. Since the instrument does not use magnetic field and triggers on any contiguous 3 pairs of x and y layers, all species of cosmic ray coming from almost 4π solid angle are recorded with a minimum bias due to the detector geometry. It is particularly important that GLAST-BFEM has measured albedo gamma ray fluxes down to $\sim$10 MeV at large zenith angles. The model has also incorporated published measurements including those by the AMS collaboration [17] and the BESS collaboration [18] in the limited energy and zenith-angle ranges data are available [15]. We believe this model best represents the cosmic ray background PoGO.

TABLE II
DETECTOR PARAMETER CHOICES

Parameter	Value
Max diagonal of PDC's hexagonal cross-section	3.2 cm
Length of fast plastic scintillator rod	20 cm
Length of slow plastic scintillator tube	60 cm
Thickness of lead foil	50 μm
Thickness of tin foil	50 μm
Thickness (average) of BGO: L3	3 cm
Thickness of BGO in SAS	3 cm
Number of PDCs	397

In the analysis we assumed the Crab Nebula flux to be $0.14\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ in the 50 keV band at 50 keV [19] before attenuation by the residual atmosphere. In Monte Carlo simulation, we assumed it to be $3\ \mathrm{g/cm}^2$.

Scintillation light yield is modelled with Poisson statistics with the mean set at $0.5 \times E_r$, where E_r is the energy deposit (in keV) in the fast plastic scintillator. This model results from preliminary tests described below.

Based on theses simulation studies lengths of the fast plastic scintillator rods and the slow plastic scintillator hexagonal tubes have been chosen to be 20 cm and 60 cm, respectively (see Fig.2). The FOV is $\sim$3 deg square or ~ 2.5 msr and matches the source-confusion limit for the PoGO design. A thin (50 μm thick) sheets of lead (or lead + tin) have been added around the hexagonal tubes to reduce background due to downward albedo gamma rays.

The design shows an outstanding signal-to-background ratio between 25 and 50 keV (Fig.6). For the geometric area of the design, $\sim$1787 cm^2, the instrument gives an effective area of 274 cm^2 with modulation of 23% averaged over a Crab spectrum between 25 and 200 keV. We confirmed the predicted modulation factor with a setup made of 7 fast scintillator rods and a 90 degree Compton scattered polarization source at $\sim$50 keV.

IV. Expected Performance of the Instrument

The lower bound of the energy coverage is set by the minimum measureable recoil electron energy, which is in turn determined by the photo-electron yield per keV of energy loss. We have carried out research and development work to improve this quantity. These include studies on the reflector used to wrap scintillators and the surface treatment of the bottom BGO. Improvement on the quantum efficiency of the photon sensor is also important. We discuss its future prospect later.

Table 3 shows relative pulse heights obtained with 3 light reflector choices for the fast plastic scintillator. In this comparison, the B400 scintillator made by Bicron and the H7179 PMT made by Hamammatsu Photonics are used. Preselected "high-quality" multilayer reflective film by 3M, VM2000, gives the best result [20].

The diameter of the PMT is chosen to be 1 inch for the final detector implementation. Light from the plastic scintillators must be transmitted through the BGO crystal before

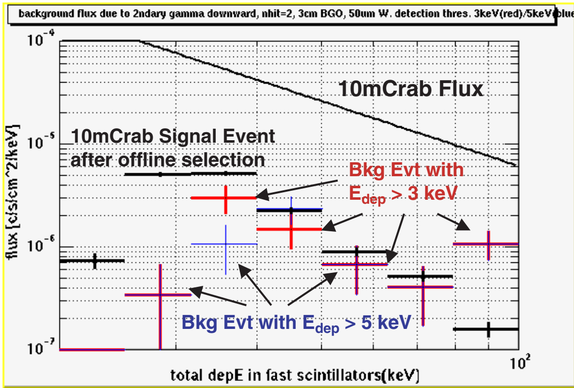

Fig. 6. Background due to cosmic rays including albedo gamma rays. The coincidence rate ($E_{deposit} > 3$ keV) due to the background (grey cross) is smaller than that of a 10mCrab source (black cross) between 20 and 80keV. Shown in the same figure is that the background does not change much even if $E_{deposit}$ is raised to 5 keV (thin cross).

reaching the photocathode; some fraction of light from the fast scintillator rod propagate upward to the hexagonal well (see Figs.1 and 2). Preliminary measurements have shown that the transmission efficiency through the BGO is about 75% [21] and the average number of photo-electrons per keV of energy loss by an electron is around 0.5 in the final setup as already stated earlier.

The final energy of scattered gamma ray in a Compton scattering is quite high as shown in Fig.5. The situation holds even if the gamma ray undergoes another Compton scattering. Hence the instrument can clearly be triggered on a 20 keV energy deposition or on 10 photo-electrons (average) at the PMT at the photo-absorption site. The final energy of recoil electron is very low and its detectability is determined by the software threshold set at Level-1 trigger. Simulation study shows that Poissonian statistical fluctuation allows the instrument to detect the recoil electron down to incident gamma ray energies of ∼25 keV with a reasonable efficiency. Although the energy resolution will be poor even at 20keV ($fwhm \sim 70\%$), confusion between the photo-absorption and the scattering sites is expected to be small. We note also that confusion between the two sites does not affect the polarization measurement.

Attenuation in the residual air of ∼3 g/cm^2 (our default value) also sets the lower energy limit for the incident gamma rays at around 25 keV.

Monte Carlo studies incorporating all of above facts and parameters predict PoGO can decisively select, by 20σ, a pulsar model out of the Polar Cap Model [22], the Caustic Model [23], and the Outer Gap Model [24] in a 6-hour balloon observation of the Crab Pulsar (see Fig.7). It can also measure polarization of hard X-rays coming from several accreting Galactic Black Holes including Cygnus X-1, to a few % to 10% level.

V. Future Prospect

We are pursuing two possible paths to lower the minimum detectable recoil electron energy and increase the effective area of polarization measurement: by improving the PMT's

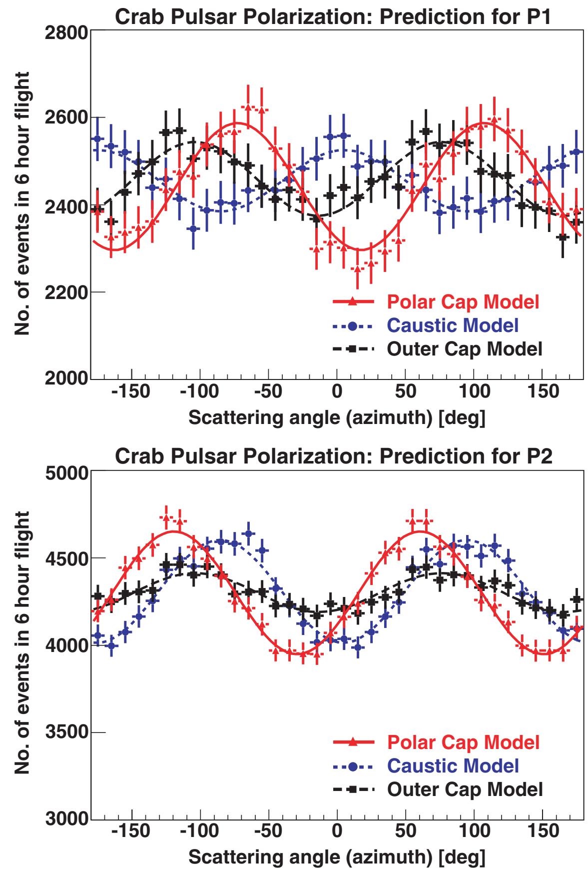

Fig. 7. Predicted Angular Distribution of 3 Models for the 1st pulse (upper panel) and the 2nd pulse (lower panel) of Crab Pulsar: Polar Cap Model (grey solid) Caustic Model (grey dot) and Outer Cap Model (black dash).

photocathode quantum efficiency, and by replacing the PMT with the Avalance Photo-Diode (APD).

In the first approach, a few PMTs with non-planar photocathode (R7899-EG and R7899-EGP) by Hamamatsu Photonics have been studied together with Bicron's plastic scintillator BC430. They give ∼10-30% more photo-electrons when comapared with those with normal photo-cathode [25] [21].

On the second approach, several types of APDs have been tested with plastic scintillator [26]. We favor the APD S8664-55 by Hamamatsu Photonics because it operates at around 300 voltage. At present, however, the sensitive area is small ($\sim 5\times5$ mm^2) and the detectable minimum energy reaches ∼1 keV only when cooled down to −30°C. Keeping an array of APDs at −30°C in a short balloon experiment poses a major challenge. This path will become very attractive, however, when PoGO is upgraded to a satellite project.

References

[1] M. C. Weisskopf et al., ApJ, 208, p.L125 (1976); M. C. Weisskopf et al., ApJ, 220, p.L117 (1978); E. H. Silver et al., ApJ, 225, p.221 (1978)
[2] E. Costa et al., Nature, 411, 662 (2001)
[3] T. Mitani et al., IEEE-NS (this symposium proceedings)
[4] F. Lei, A. J. Dean and G. L. Hills, Space Sci. Reviews Vol.82 Ns.34, p.309 (1997)

TABLE III

RELATIVE LIGHT YIELD WITH 3 CHOICES OF REFLECTORS

	Relative Pulse Height		
Gamma source	Teflon sheet	VM2000(standard)	VM2000(selected)
Cd(22keV)	1.0	1.15	1.17
Fe(5.9keV)	1.0	1.19	1.24

[5] A. J. Dean, in Int. Advanced School "Leonardo da Vinci" (2002)
[6] T. Kamae, et al., SPIE, Vol. 1734, 2 (1992); IEEE Trans. NS-40(2), 204 (1993)
[7] T. Takahashi, et al., IEEE Trans. NS-40(3), 890 (1993)
[8] S. Gunji, et al., ApJ, 397, L83 (1992); S. Gunji, et al., ApJ, 428, 284 (1994); S. Miyazaki, et al., Pub. Astron. Soc. Japan, 48, 801 (1996); N. Yamasaki, et al., ApJ, 481, 821 (1997)
[9] T. Kamae, et al., SPIE, Vol. 2806, 314 (1996)
[10] K. Makishima, et al., ASP Conf. Proc. 251, eds. H. Inoue and H. Kunieda, Astr. Soc. of the Pacific, 564 (2001)
[11] W. R. Nelson, H. Hirayama, and D. W. O. Rogers, SLAC-Report 265 (1985)
[12] R. Brun, et al., CERN Data handling Division Report DD/EE/84-1 (1987); K. Amako, et al., 1994, Proc. of CHEP94, LBL-35822 CONF-940492 (1994)
[13] Y. Namito, S. Ban, and H. Hirayama, NIM A332, 277 (1993)
[14] Y. Namito and H. Hirayama, KEK-Internal Report 2000-4 (2000)
[15] T. Mizuno, et al., Proc. of HEAD Meeting, No.B17.048 (2002)
[16] D. J. Thompson et al., IEEE Trans NS-49, 1898 (2002); T. H. Burnett et al., IEEE Trans NS-49, 1904 (2002);
[17] J. Alcaraz et al.,Phys. Lett. B472, 215 (1999); Phys. Lett. B484, 10 (2000); Phys. Lett. B490, 27 (2000);
[18] T. Sanuki, et al., ApJ 545, 1135 (2000)
[19] L. Kuiper, et al., Astron. & Astrophys., 378, 918 (2001)
[20] S. Gunji et al., Presentation in COSPAR 2002 (2002)
[21] M. Suhonen, Diploma Thesis (Royal Inst. of Tech., Stockholm) (2003)
[22] S. Sturner, C. Dermer, and F. C. Michel, ApJ, 445, 736 (1995); J. Daugherty and A. Harding, ApJ, 458, 278 (1996)
[23] J. Dyks and B. Rudak, ApJ, submitted (astro-ph/0303006) (2003)
[24] K. S. Cheng, C. Ho, and M. A. Ruderman, ApJ, 300, 500 (1986); R. Romani and I. Yadigaroglu, ApJ, 438, 314 (1995); R. Romani, ApJ, 470, 469 (1996)
[25] M. Itatani, Master Thesis (Yamagata Univ., Yamagata, Japan) (2003)
[26] T. Ikagawa et al., NIM A (in press)