

Observation of Polarization in Hard X-Ray Region with PHENEX Polarimeter

Kishimoto Y.¹, Gunji S.¹, Ishikawa Y.¹, Takada M.¹, Toukairin N.¹, Tanaka Y.¹, Tokanai F.¹, Sakurai H.¹, Mihara T.², Sato T.², Hayashida K.³, Anabuki N.³, Ota M.³, Tsunemi H.³, Narita T.⁴, Saito Y.⁵, Kohama M.⁶, Suzuki M.⁶, Kishimoto S.⁷

¹ Yamagata University, Yamagata, Yamagata, Japan

² RIKEN, Wako, Saitama, Japan

³ Osaka University, Toyonaka, Osaka, Japan

⁴ College of the Holy Cross, Massachusetts, USA

⁵ JAXA/ISAS, Sagamihara, Kanagawa, Japan

⁶ JAXA/ISAS, Tsukuba, Ibaraki, Japan

⁷ KEK, Tsukuba, Ibaraki, Japan

E-mail(KY): kishimo@ksprite.kj.yamagata-u.ac.jp

ABSTRACT

On X-ray and hard X-ray astronomy, the polarization is the last key. It is very useful to understand the radiation mechanism of gamma-ray bursts and pulsars, magnetic structure of supernova remnants, space-time curvature near black hole, and so on. However, the observation for the polarization has been rarely carried out for about 30 years since the observation of the Crab Nebula in X-ray region. It is because of the difficulty for development of the polarimeter with high sensitivity. We have been developing a hard X-ray polarimeter with high sensitivity, called as a PHENEX (Polarimetry for High ENERgy X rays) polarimeter. The PHENEX polarimeter is Compton scattering type polarimeter sensitive to the energy range from 40 keV to 200 keV and is constructed assembling several detectors called as “unit counter”. The unit counter is a detector utilizing Compton scattering and it has a modulation factor of 53% and a detection efficiency of 20% at 80keV. We constructed prototype PHENEX polarimeter with four unit counters and carried out a preliminary observation of the Crab Nebula on Jun. 13th 2006 as a balloon-borne experiment. Though we confirmed that the PHENEX detected hard X rays from the Crab Nebula with significance of 8σ , the degree and the direction of the polarization could not be determined with high accuracy because the attitude control system does not function correctly.

Now we are improving the performance of the ACS and the polarimeter to realize the observation of the Crab Nebula with higher accuracy in the next balloon-borne experiment. In this paper, we will present the follows: 1) summary of the PHENEX polarimeter and preliminary observation of Crab Nebula; 2) fix of the ACS trouble; 3) improvement of the PHENEX polarimeter; 4) expected performance for the next observation.

KEY WORDS: hard X ray, polarimeter, PHENEX

1. Introduction

In X-ray astronomy, the information on energy spectrum, timing, and imaging has been utilized to understand the nature of the universe. Left out of these measurements to date is polarimetry, yet the observation of polarization brings us invaluable information such as space-time curvature near black hole, radiation mechanisms in pulsars, and the magnetic structure of supernova remnants (P. A. Connors et al. 1980)(J. Dyks et al. 2004). Further, it is also useful for understanding the radiation mechanism in gamma-ray bursts (W. Coburn et al. 2003).

Despite its potential usefulness, no significant x-ray polarization measurement has been carried out for about 30 years since the observation of the Crab Nebula (M. C. Weisskopf et al. 1978)(J. P. Hughes et al. 1984). This is because of the difficulty of developing an X-ray polarimeter with high sensitivity. Since the origin of the polarization is often due to non-thermal radiation processes such as synchrotron radiation, observations in the hard-X-ray region are possibly more important than that for the soft-X-ray region; it is expected that the degree of polarization in the hard X-ray region would be higher than

that at lower energies (F. Lei et al. 1997). For the above reasons, we have been developing a hard X-ray polarimeter with high sensitivity (S. Gunji et al. 1994)(H. Tomita et al. 1996), called PHENEX (Polarimetry for High EN-Ergy X rays) polarimeter (T. Suzuki et al. 2006)(Y. Kishimoto et al. 2007).

The PHENEX polarimeter is Compton-scattering-type polarimeter sensitive in the energy range from 40 keV to 200 keV and is constructed in a modular fashion with an array of "unit counters". After we measured the performance of one unit counter using the highly polarized beam of BL14A in KEK, we have constructed the PHENEX polarimeter with four unit counters and then carried out balloon-borne experiment on June 13, 2006 to observe the Crab Nebula.

In the following sections, we present summaries of the PHENEX polarimeter and preliminary observation of Crab Nebula in 2006. Moreover, we also explain the status of the preparation for the next observation and show the expected performance for it.

2. Unit Counter

The unit counter consists of 36 (6×6) pieces of plastic scintillator surrounded by 28 pieces of CsI(Tl) scintillator. These 64 pieces of the scintillator are read out by one multianode photomultiplier (MAPMT) with 64 channels developed by HAMAMATSU Photonics Inc. Fig. 1 shows a schematic view for the unit counter. The pixel size of the multianode photomultiplier is $6.0 \times 6.0 \text{ mm}^2$ and the size of scintillators is $5.5 \times 5.5 \times 40 \text{ mm}^3$. As incident hard X ray enters into one of the plastic scintillator, Compton scattering occurs and then the scattered hard X ray is absorbed by one of the surrounding CsI(Tl) scintillators. The azimuthal scattering angle depends on the polarization direction of the incident hard X rays as shown in Eq. 1. Since these scintillators are

$$\frac{d\sigma}{d\Omega} = \frac{r_0^2 k^2}{2 k_0^2} \left(\frac{k_0}{k} + \frac{k}{k_0} - 2\sin^2\theta\cos^2\phi \right) \quad (1)$$

- r_0 : classical radius of electron
- θ : scattering angle for incident direction
- ϕ : azimuthal scattering angle for polarization vector
- k_0 : energy of incident hard X ray
- k : energy of scattered hard X ray

segmented, the 2-dimensional scattering direction can be measured and hence the information on the polarization of the incident hard X rays can be obtained (Fig. 2). The instrument field of view is constrained to 4.8 degrees (FWHM) by a collimator made of molybdenum (1 mm thickness). The side of the unit counter is covered by graded passive shields made of Pb (2mm thickness) and

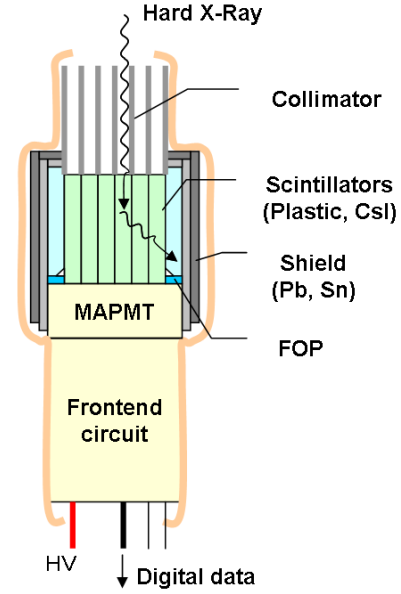


Fig. 1. The schematic view of the unit counter. An incident hard X ray is scattered by one of plastic scintillator and absorbed by one of CsI(Tl) scintillator, respectively.

Sn (1mm thickness). Each energy deposit in the plastic and CsI scintillators is read out by the MAPMT, and the signals of each pixel are fed through charge-sensitive preamplifiers and shaping amplifiers to an Analog to Digital Conversion (ADC) system for digitization.

The unit counter performance has been investigated in detail using a polarized hard X-ray beamline (Beam Line 14A) in KEK, and it has been recognized that the unit counter has a modulation factor of 53% and a detection efficiency of 20% at 80keV. In Table 1, the basic parameters of the unit counter are summarized.

Sensitive area [cm^2]	11
Field of view(FWHM) [degree]	4.8
Size [cm^3]	$6 \times 6 \times 25$
Sensitive energy range [keV]	40 to 200
Detection efficiency [%]	20 (80keV)
Modulation factor [%]	53 (80keV)

Table 1. Basic parameters of the unit counter.

3. PHENEX Polarimeter

In 2006, we constructed a balloon-borne flight model, PHENEX, with four unit counters to observe the Crab Nebula. The instrument configuration for this flight is shown in Fig. 3. In the center of the four symmetrically-arranged unit counters, the counter with CsI(Tl) scintillator ($34 \times 34 \times 10 \text{ mm}^3$) is installed to monitor the flux from the Crab Nebula and then is called "monitor counter". The monitor counter has the same collimator

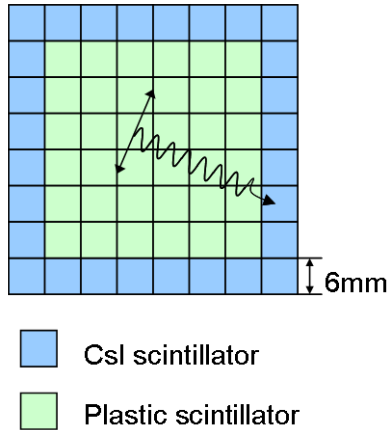


Fig. 2. The top view of scintillators. The solid arrow and the wavy arrow represent the direction of polarization of an incident X ray and the direction of the scattered X ray, respectively.

as that of the unit counters and is co-aligned with them. It can be also used to confirm the correct function of attitude control system. The monitor counter and the four unit counters are all installed inside CsI(Tl) active shields and the whole assembly is housed in a pressure vessel and can rotate along the line of sight. This rotation is necessary to permit removal of systematic effects such as spurious modulation due to individual differences in the scintillators.

Initiated by a trigger signal from any of the four unit detectors or the monitor counter, the signals of all 266 channels (64×4 channels), the monitor counter (1 channel), and active shields (9 channels) are all digitized by the front-end circuits. The information is processed by a VME-based data acquisition system and it is saved in data storage (USB memory) with timing information from GPS system. A data-flow diagram is shown in Fig. 4.

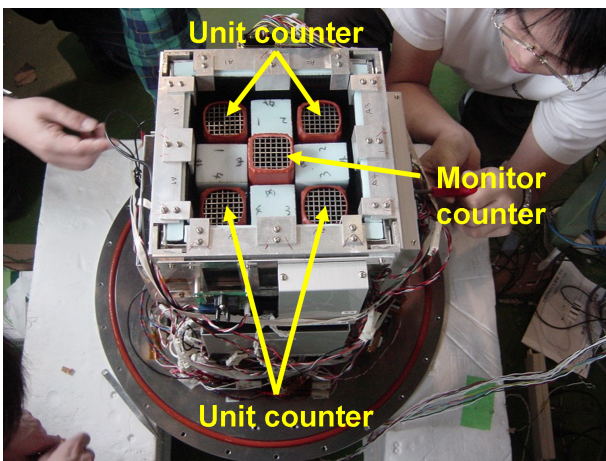


Fig. 3. The flight detector system. Four unit counters and one monitor counter are installed inside CsI(Tl) active shields.

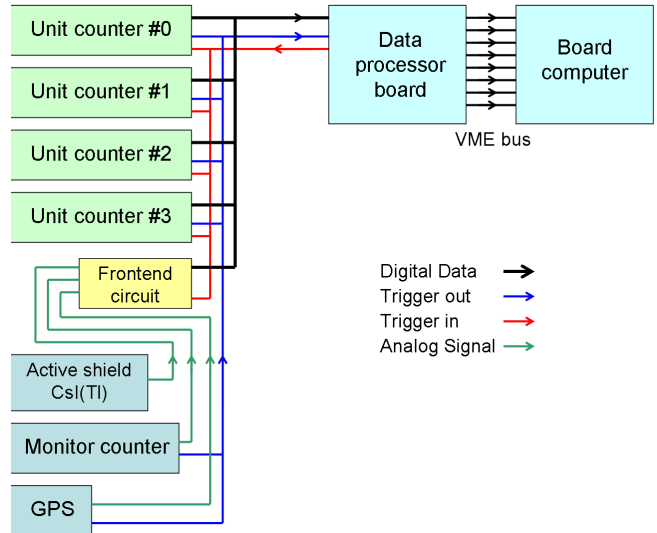


Fig. 4. The data flow diagram of the detector system. When one of the unit counters or the monitor counter generates a trigger signal, the signals of CsI(Tl) active shields are read out by the data processor board at the same time.

During flight, a sun sensor was used for the monitor and control of the line of the sight for the PHENEX polarimeter. The sun sensor is a pinhole camera with a two-dimensional position-sensitive photodiode. Its field of view is about $30^\circ \times 30^\circ$ and it can determine the attitude of the polarimeter to an accuracy of about 1 degree. The attitude control system (ACS) has the ability to track the Crab Nebula automatically using the output signal from the sun sensor.

4. Balloon Experiment

The balloon-borne experiment was carried out on June 13th, 2006 to observe the Crab Nebula after launch from the Sanriku Balloon Center. We achieved a level flight for 6 hours at the altitude of about 38 km. The detector system operated well without any serious problem over the duration of the flight and the data were saved safely. However, the ACS did not function correctly and hence the line of sight unfortunately wandered around the Crab Nebula. However, as the sun sensor operated well, we can obtain the necessary information about the pointing direction of the PHENEX polarimeter as a function of time. After all, we succeeded in observing the Crab Nebula for about one hour and also a blank region of the sky for about one hour. The region of the blank sky corresponds to the same elevation and azimuth as that of the Crab Nebula during its observation period. From the data, we confirmed that PHENEX polarimeter detected hard X rays from the Crab Nebula with a significance of 8σ . Then, we carried out polarization analysis and the result of it is shown in Fig. 5. As shown in this figure, the degree and the direction of the polarization can not be

determined with high accuracy. However, it is important advance for polarimetry in hard X-ray region taking into account that the polarization of the Crab Nebula had not been observed in hard X-ray region.

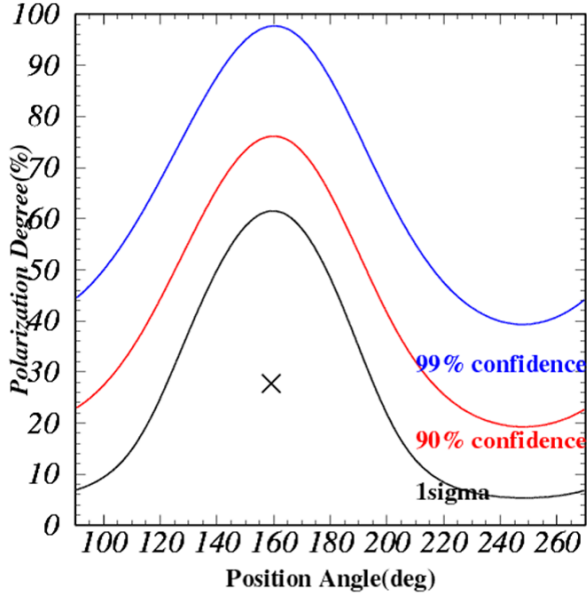


Fig. 5. The result of polarization analysis. The X-axis and Y-axis correspond to the polarization direction and degree, respectively. These lines show contour lines for three error levels (1σ , 90% confidence, 99% confidence).

5. Preparation for the Next Balloon Experiment

To determine the degree and the direction more accurately on the next balloon-borne experiment, it is important to fix the trouble of ACS and to improve the performance of the PHENEX polarimeter.

5.1. Fix of the Trouble on the ACS

First, we investigated the problem on ACS, and found that one of the important parameters used in the computer program of the ACS was not set to correct value. After the set to correct parameters, we investigated the performance of the pointing in use of computer simulation. Fig.6 is a typical result of the simulation. The x-axis and y-axis correspond to the elapsed time from the beginning of the control and the angular difference between the direction of the target object and the pointing direction, respectively. Though the gondola wobbles around the target object for about 3 minutes, the difference gradually converges. Finally it is stabilized to less than 0.1 degrees. Although we tried the simulation with some patterns of parameters, the behavior was basically similar to the above example. Consequently, we

recognized that the bug-fixed ACS can point the target object with the accuracy below 0.1 degrees in a few minutes. Now we are investigating the detail performance using the actual ACS.

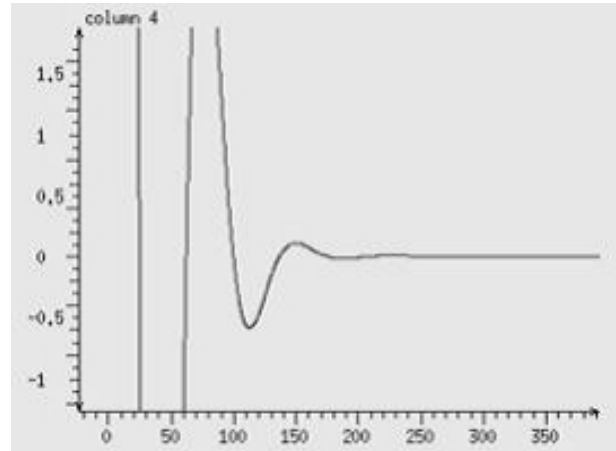


Fig. 6. A result of the simulation for our ACS. The X-axis shows the elapsed time since the beginning of the simulation. The Y-axis corresponds to the difference of azimuthal angle between the gondola and the target object. In this simulation, the initial angular difference between the gondola and the target object is set to 90 degrees, and we assume that the target object moves at the speed of 1 degree/sec constantly.

5.2. Improvement of the PHENEX Polarimeter

In parallel, we are improving the PHENEX polarimeter now. In the first place, we are manufacturing four more unit counters to install eight unit counters to the PHENEX polarimeter (Fig.7). It enlarges the detection area of the PHENEX polarimeter and achieves the effective area of two times more than previous one. Thus, statistical advantage for the determination of the polarization degree and direction can be obtained. Furthermore, this improvement also has another merit that signal-to-background ratio goes up. This merit is derived from the following. The previous version of the PHENEX polarimeter has empty slots as shown in Fig.3 to install more unit counters. Through the space, external background could hit the unit counters. Because this improvement fills the space with unit counters and the unit counter can also work as active shields for neighboring ones, much reduction of background should be realized and then signal-to-background ratio goes up. From the data on previous balloon-borne experiment and preliminary computer simulations considering the hard X-ray flux of the Crab and the background, it is expected that the signal-to-background ratio will go up to 1.0:0.6.

Secondly, we also improved the unit counter itself. Although the front-end circuit adopted for unit counter is compact and very useful for reading the MAPMT signals of 64 channels simultaneously, detection efficiency

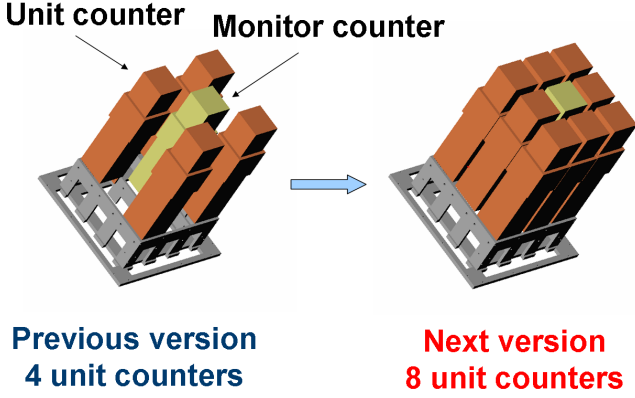


Fig. 7. Improvement of the PHENEX polarimeter. The number of unit counters will be doubled and the empty space in the previous version is also filled with unit counters. These have two merits as follows: 1) enlargement of the detection area; 2) improvement of the signal-to-background ratio. 2) is because that the unit counter can also work as active shields for neighboring ones.

around threshold is somewhat low. This caused deterioration of detection efficiency around 40keV in the balloon-borne experiment in 2006. Therefore, we optimized the gain of the circuit and the applied voltage to the MAPMTs to improve the detection efficiency around 40keV. In the result, detection efficiency at 40keV was improved to be about 4 times. Furthermore, we will enhance the passive shield around unit counter to reduce the background level as shown in Fig. 8.

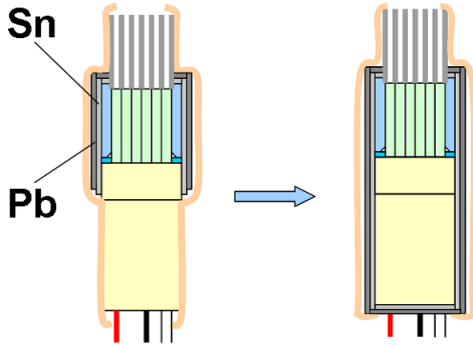


Fig. 8. Reinforcement of passive shield around unit counter. We will enhance passive shield and enclose unit counter wholly with it except incident window.

6. Expected Performance

So we estimated the expected performance for the enlarged PHENEX polarimeter by Eq. 2 of MDP (Minimum Detectable Polarization). For this, we took the following assumptions into consideration : 1) 3 hour's

$$MDP = \frac{429}{A\eta SM} \sqrt{\frac{A\eta S + B}{T}} \quad (2)$$

A	: Detection area [cm ²]
S	: Signal Count Rate [sec ⁻¹ cm ⁻²]
η	: Detection efficiency
M	: Modulation factor
B	: Background Count Rate [sec ⁻¹]
T	: Observation time [sec]

observation of the Crab Nebula at the level flight with enlarged PHENEX polarimeter (8 unit counters); 2) 1.0:0.6 as signal-to-background ratio calculated from a preliminary computer simulation using GEANT4; 3) 0.1cps as signal rate per one unit from the data on previous balloon-borne experiment. As the result, the minimum detectable polarization is estimated to be 11% for next observation. Furthermore, we calculated by another computer simulation the accuracy of the determination for the degree and the direction of the polarization. So we recognized that the degree and the direction of the polarization can be determined with accuracy of about $\pm 4\%$ and ± 9 degrees respectively if the polarization degree in hard X-ray region is 30%. In above calculations, we have not yet considered the effects of the follows: 1) improvement of detection efficiency around 40 keV due to the optimization of the circuit gain and the voltage applied to MAPMT; 2) improvement of signal-to-background ratio due to the reinforcement of passive shield. Therefore, more higher performance will be expected if we include these effects in the calculations.

7. Conclusion and Future Works

We have been developing a hard X-ray polarimeter with high sensitivity, called as a PHENEX (Polarimetry for High ENergy X rays) polarimeter. We carried out preliminary observation for the polarization of the Crab Nebula in June 2006 with the polarimeter. Although the PHENEX polarimeter detected hard X rays from the Crab with a significance of 8σ , the degree and the direction of polarization with high accuracy could not be determined in this observation.

Now we are improving the performance of the ACS and the polarimeter to realize the observation of the Crab Nebula with higher accuracy for the next balloon-borne experiment. First, we has fixed the bug of ACS and are performing laboratory experiments to demonstrate that it can point the target object with the accuracy below 0.1 degrees. Secondly, we are also improving the PHENEX polarimeter. In particular, we are constructing the PHENEX polarimeter with eight unit counters to enlarge the detection area as twice and to

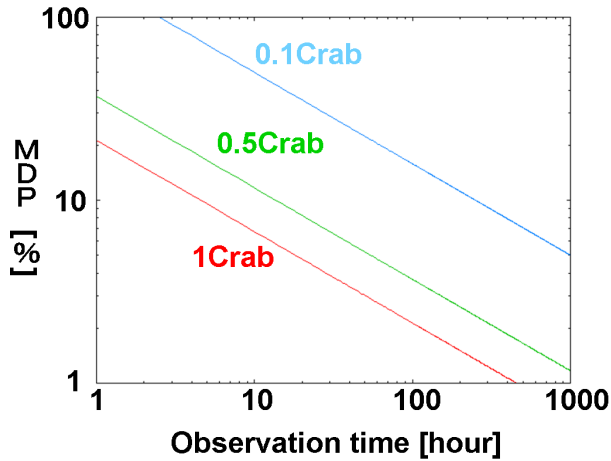


Fig. 9. Expected MDP for next version of PHENEX polarimeter. This is calculated on the following assumptions: 1) 3 hour's observation of the Crab Nebula at the level flight with enlarged PHENEX polarimeter (8 unit counters); 2) 1.0:0.6 as signal-to-background ratio calculated from a preliminary computer simulation using GEANT4; 3) 0.1cps as signal rate per one unit from the data on previous balloon-borne experiment.

improve signal-to-background ratio. Moreover, we already have developed the new version of unit counter with higher detection efficiency around 40 keV due to the optimization of the circuit gain and the voltage applied to MAPMT. Moreover, we will also enhance the passive shield of unit counter to go up signal-to-background ratio. We estimated the expected performance for the next observation assuming 3 hour's observation with enlarged PHENEX polarimeter and the signal-to-background ratio estimated from computer simulation. As the result, it was recognized that the polarization of Crab Nebula was detectable with the significance of 3 sigma if Crab Nebula was polarized more than 11%. Furthermore, we calculated by another computer simulation the accuracy of the determination for the degree and direction of the polarization. As the result, it was recognized that these can be determined with accuracy of about $\pm 4\%$ and ± 9 degrees respectively if the polarization degree in hard X-ray region is 30%.

Now we are preparing for the next observation in 2009. After that, we will observe some sources that are bright in hard X-ray region. If long-duration-flight balloon is put to practical use, the MDPs for sources brighter than 0.5 Crab and 0.1 Crab will go up to a few percent and about 10%, respectively. Moreover, we are planning to load a modified PHENEX polarimeters to a small satellite named "POLARIS" as a focal-plane detector of a hard X-ray mirror.

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