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The PHENEX Experiment Results in 2006 and Future Plan

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To open a new window for hard X-ray astronomy, we have developed a hard X-ray polarimeter called as PHENEX (Polarimetry for High ENErgy X rays). The PHENEX polarimeter is constructed by assembling Compton scattering type polarimeters called as a unit counter, which can achieve the modulation factor and the detection efficiency of 53% and 20% at 80 keV, respectively. Installing four unit counters, we have carried out balloon-borne experiment in Jun.13 2006 to preliminarily observe the polarization of the Crab Nebula in hard X-ray band. It successfully operated on the level flight and observed the Crab Nebula for about one hour. From the analysis of the data, the following three results have been obtained. 1) The ratio of the signal from the Crab Nebula to the background from the blank sky was estimated to be about 1:2.2. 2) The PHENEX polarimeter did not make spurious modulation more than 1.8% on the observation of blank sky. 3) The degree and the direction of the polarization for the Crab Nebula were determined to be 33 ± 26% and 154 ± 43 deg, respectively. This result for the polarization is not inconsistent with the previous result by OSO 8 in X-ray band nor the recent one by INTEGRAL in gamma-ray region. Since more precise measurements in hard X-ray band are necessary for the study of the Crab Nebula, we will carry out balloon-borne experiment again in 2009 by the improved PHENEX polarimeter.

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1. PHENEX Polarimeter

Observation of polarimetry was an unexplored field on high-energy astrophysics comparing the observations of spectroscopy, timing, and imaging. The reason was due to the difficulty of developing polarimeters with high sensitivity in higher energy band than X ray. However, by drastic advance of detector technologies such as micro-pixel gas detector or multi-anode photomultiplier with high quantum efficiency, the situation has recently been much changing because the use of them makes it possible to develop polarimeters with high sensitivity[1][2]. Moreover, the polarization detection for the Crab Nebula by SPI detector of INTEGRAL satellite has played a role as priming to awaken to the physical importance of the polarization observation[3]. In the present situation, it is required to realize more precise observation of the polarization for typical high-energy stellar objects such as the Crab Nebula/Pulsar and Cygnus X-1, and then to manifest the importance of polarization measurements for the study of high-energy stellar objects. So, we have developed a hard X-ray polarimeter named as PHENEX (Polarimetry of High ENErgy X rays) to open the new window for hard X-ray astronomy.

1.1 Unit Counter

The PHENEX polarimeter is Compton scattering type polarimeter. It consists of bunch of the detectors named as a unit counter. The schematic view of the unit counter is shown in Fig.1. The unit counter consists of 36 (=6$\times$6) pieces of plastic scintillator surrounded by 28 pieces of CsI(Tl) scintillator[2][4]. These scintillators are mounted on a MAPMT (H8500) with 64 channels, which is manufactured by Hamamatsu Photonics Inc. Above the scintillators, the collimator made of molybdenum is installed to constrain the field of view to 4.8 degrees (FWHM). On the side of the unit counter, graded passive shields made of Pb (2 mm thickness) and Sn (1 mm thickness) are attached. Also above the CsI(Tl) scintillators, the graded passive shields are laid to prevent incident hard X rays from directly entering to CsI(Tl) scintillators. As incident hard X ray enters to one of the plastic scintillator, the hard X ray is scattered. Then the scattered hard X ray is absorbed by one of the CsI(Tl) scintillator. Detecting the scattering angle, the information on the direction of the polarization can be obtained. The energy range of the unit counter is from 40 keV to 200 keV and the geometrical area of one unit counter is about 11 cm^2. We investigated the modulation factor and the detection efficiency using beamline BL14A in KEK. Then we confirmed that it can obtain the modulation factor of 53% and the detection efficiency of 20% at 80 keV, respectively[2].

1.2 Flight Model of the PHENEX Experiment in 2006

We have constructed a balloon-borne flight model of the PHENEX polarimeter with four unit counters and a monitor counter surrounded by active shields of CsI(Tl) scintillator (17 mm thickness) and passive graded shields of Pb (2 mm thickness) and Sn (1 mm thickness). The picture of the instrument is shown in the left figure of Fig.2. The monitor counter is made of CsI(Tl) scintillator (34 $\times$ 34 $\times$ 10 mm^3) and a PMT. Above the monitor counter, the same collimator as that of the unit counter is mounted and it is co-aligned with them. The monitor counter is only used to monitor the flux from the Crab Nebula. The whole instrument is housed in a pressure vessel. In the right figure of Fig.2, the picture of the pressure vessel installed in the gondola is shown. The size of gondola is about 1.5m^3 and the total weight is about 250kg. The pressure vessel can rotate

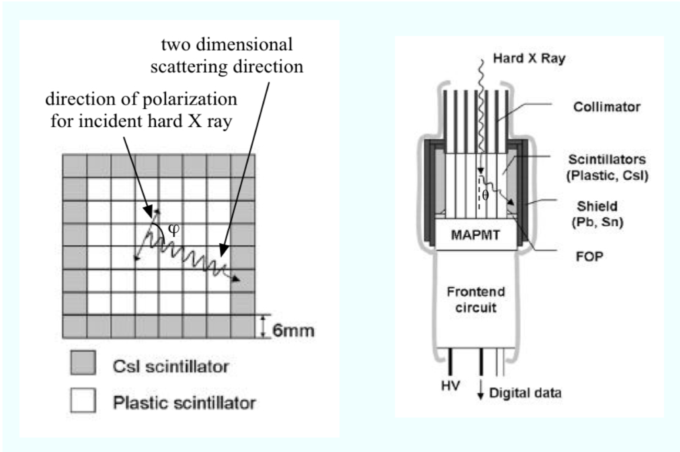

Figure 1: The left figure and the right figure show the schematic top view and side view of the unit counter, respectively.

around line of the sight to reduce systematic effects such as spurious modulation due to individual differences in the scintillators. The line of sight of the polarimeter can be controlled by an attitude control system (ACS). The ACS of PHENEX polarimeter has a sun sensor with the field of view 30 degrees $\times$ 30 degrees and the actuator. With the sun sensor and the actuator, it is possible to track the Crab Nebula automatically.

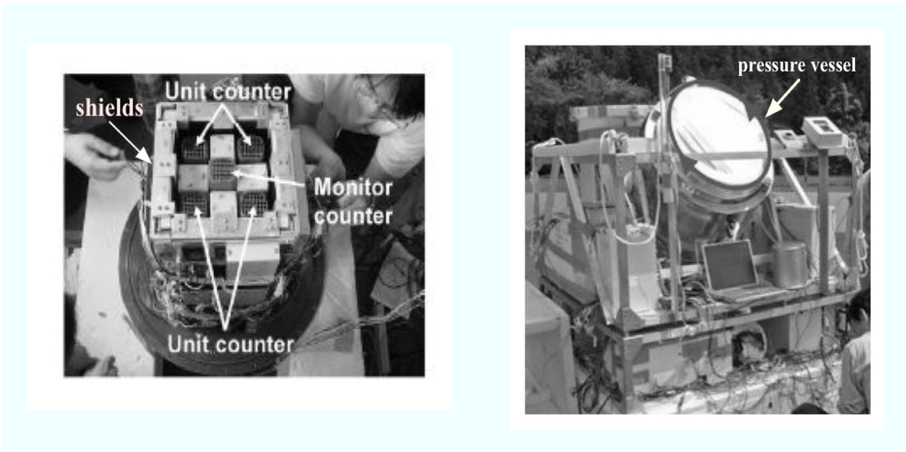

Figure 2: The left figure is the PHENEX polarimeter with four unit counters and the monitor counter. These detectors are surrounded by active shields made of CsI(Tl) and passive graded shields. The whole instrument is housed in the pressure vessel shown in the right figure.

2. Balloon-borne Experiment in 2006

On June 13th, 2006, we launched the PHENEX polarimeter and achieved a level flight for 6 hours at an altitude of about 38km. Though the polarimeter operated well over the duration of the flight, the actuator of 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 identify with the latter data analysis the direction that the PHENEX polarimeter is pointed to. The left figure of Fig.3 shows the line of sight of the PHENEX polarimeter on the observation of the Crab Nebula. The central position of this figure and the circle correspond to the line of the sight for the PHENEX polarimeter and the opening angle of 4.8 degrees (FWHM), respectively. The dotted points are the positions of the Crab Nebula for the equatorial coordinates and one point per one second is put. Considering the data for the pointed direction and the opening angle (4.8 degrees) of the collimator, the acceptance of the PHENEX polarimeter for hard X rays from the Crab Nebula was calculated for each time. The results are shown in the right figure of Fig.3 as dashed histogram. For about 80 minutes, the acceptance was above about 50%.

To confirm that the monitor counter detected the flux from the Crab Nebula, the counting rates for the monitor counter are investigated. The counting rates are also shown in the right figure of Fig.3 as dotted histogram. As shown in this figure, the counting rates of the monitor counter well correlate to the acceptance. The increase of the counting rates at the acceptance above 50% is about 0.3 Hz and the value was consistent with the expected flux from the Crab Nebula. So we used as 'on-source' the data for the interval when the acceptance is above 50%. On the other hand, we also

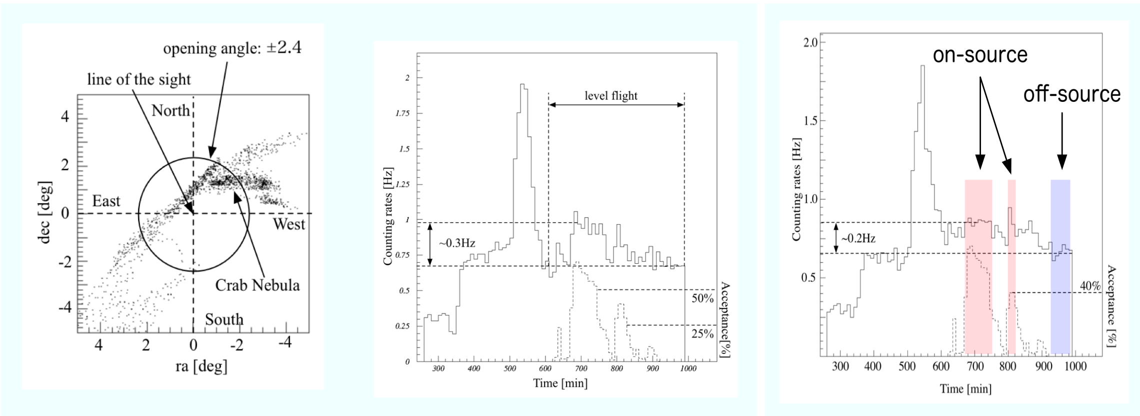

Figure 3: The left figure shows the line of the sight for the PHENEX polarimeter on the observation of the Crab Nebula. In the cental figure, the acceptance of the PHENEX polarimeter for the flux of the Crab Nebula and the counting rates of the monitor counter are shown as the dashed histogram and the dotted one, respectively[4]. The x axis is the time and the bin width is ten minutes. The right figure shows the counting rates for four unit counters. The increase of the counting rates on the on-source is $\sim$0.2 Hz and the significance is 8 σ.

observed the blank sky, which is at the same elevation and azimuth as that for the on-source. We used the data as 'off-source' data. We investigated the significance of the counts of the on-source for those of the off-source. The significance was calculated to be 13σ and hence we confirmed that the monitor counter detected the flux from the Crab Nebula.

We investigated the counting rates for four unit counters using the event selection method described in the previous paper[4]. In the right of the Fig.3, the counting rates are shown. As well as the counting rates for the monitor counter, the counting rates increase on the on-source and it was ~0.2 Hz for 65% acceptance due to the collimator. Considering the detection efficiency of the unit counters, the attenuation of hard X rays due to the atmosphere, and the acceptance, the counting rates are consistent with the flux from the Crab Nebula. The significance of the counting rates on the on-source was also calculated to be 8 σ and hence we confirmed that the unit counters detected the flux from the Crab Nebula. Since the counting rates for the background are 0.65 Hz and the counting rate for the Crab Nebula is ~ 0.2 Hz for 65% acceptance, the ratio of the signal from the Crab Nebula to the background from the blank sky is estimated to be 1:2.2 (0.2/0.65:0.65) if the acceptance would be 100%.

3. Data Analysis for polarization

At first, we investigated the distribution of the scattering angle for the equatorial coordinates on the off-source. Fitting the data with the following equation Eq.3.1, the best fit parameters were 204, −3.6, and 349 for A, B, and C, respectively. From these value, the degree of the modulation was calculated to be 1.8% (=3.6/204). It indicates that the PHENEX polarimeter does not make much spurious modulation.

$$y = A + B \times \sin(2x + C) \tag{3.1}$$

Before the analysis for the on-source, we investigated the effects that the line of the sight wandered around the Crab Nebula, using computer simulations with EGS4 (Electron Gamma-ray Version 4). As the resutls, we recognized that the degree of polarization is 1.24 times overestimated by the effect of the wandering though the direction is not much changed[4].

Finally, Subtracting the distribution of the off-source from that of the on-source by adjusting the observation time between the on-source and the off-source, we investigated the degree and the direction of the polarization for the Crab Nebula. In the left figure of Fig.4, the subtracted distribution is shown. The line is the fitting with the Eq.3.1. The best fitting parameters were 65.9, 14.4, and 323 for A, B, and C, respectively. The reduced χ^2 of the fitting for the degrees of

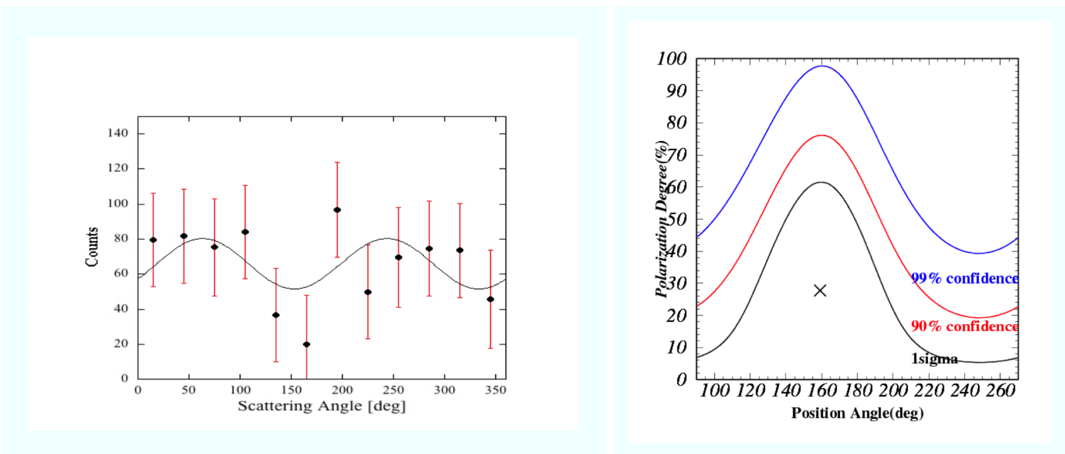

Figure 4: The left figure shows the modulation for the subtraction of the off-source from that of the on-source by adjusting the observation time between the on-source and the off-source. The right figure shows the contour plot of χ^2 with the parameters of the direction and the degree of the polarization.

freedom 9 was 0.65. Considering the modulation factor (53%) of the PHENEX polarimeter and the effect (1.24) of the wandering, the degree and the direction of the Crab Nebula are determined to be 33±26% (14.4/65.9/0.53/1.24) and 154±43 deg, respectively. Using the same data set, the contour plot of χ^2 is also made. It is shown in the right figure of Fig.4. Because each value has large error, we can not quantitatively discuss the polarization of the Crab Nebula in hard X-ray region. However, the value were not inconsistent with the previous result by OSO 8 in X-ray band[5] nor the recent one by INTEGRAL in gamma-ray region[3][6].

4. Discussions

In Table.1, we summarize the results of the polarization for the Crab Nebula above optical band. As shown in this Table.1, the polarization direction on the region within 2" is 123 deg in

Table 1: The degree and the direction of the polarization in each energy band.

Energy band	degree	direction	Observation region
optical	23%	158°	within 30" from the center (without pulsar)[8]
optical	33%	123°	within 2" from the center (without pulsar)[7]
2.6 keV	19.2%	156.4±1.4°	total region (without pulsar)[5]
5.2 keV	19.5%	152.6±4.0°	total region (without pulsar)[5]
50∼150 keV	33±26°%	154±43°	total region (with pulsar)
0.1∼1 MeV	46±10%	123±11°	total region (without pulsar)[3]
0.2 MeV<	72%<	120.6±8.5°	total region (without pulsar) [6]

the optical band[7]. Because the pulsar axis is 124±0.1 deg[9], the result for the optical band is plausible. On the other hand, the direction for X-ray and hard X-ray bands are different from the pulsar axis. However because the direction is determined with the radiation from the whole region of the Crab Nebula, the difference can be explained if the polarization direction on the region except for the center will be much different from that on the central region. It can also well explain the reason that the polarization direction on the region within 30" from the center is different from that within 2". In the case of the gamma-rays, the radiation region should be small near the central region because the lifetime of the high-energy seed electrons which emit the gamma-rays with synchrotron radiation is short and hence they can not diffuse outside from the central region. So the polarization direction of the gamma rays should be co-aligned to that on the central region. From the above reasons, the two following things are inferred; 1)Though the polarization direction on the central region is co-aligned to the pulsar axis, in the outer region it is much different from that on the central region. 2)The higher the energy of photons is, the emission region concentrates near the central region.

However, the previous observation in the hard X-ray band by Dr. Makishima etal. conflicts with the above inference[10]. They report in the paper that the emission regions for the hard X rays concentrate on the north-east and south-west parts. In this situation, the precise observation of the polarization in the hard X-ray region has physical importance as well as that of the image in the hard X-ray region.

5. Conclusions and Future Plan

We have developed the hard X-ray polarimeter named as PHENEX to establish the observation of the polarization in hard X-ray region. We have carried out the balloon-borne experiment in Jun.13th 2006 by the PHENEX polarimeter with four unit counters to preliminarily observe the polarization of the Crab Nebula. We succeeded in observing the Crab Nebula for about one hour and detecting the flux from the Crab Nebula with the significance of 8σ. Moreover, we obtained form the data analysis of the polarization that the degree and the direction of the polarization are 33 ± 26 % and $154\pm43^{\circ}$, respectively. Though the determined value has large errors, it is not inconsistent with the previous result by OSO 8 in X-ray band nor the recent one by INTEGRAL in gamma-ray region. We will carry out balloon-borne experiment again in 2009 by the PHENEX polarimeter with eight unit counters. If the degree of polarization is more than 30 %, the degree and the direction of the polarization can be determined by the improved PHENEX polarimeter with the errors less than 7 % and 14 degrees, respectively.

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