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Gamma-Ray Burst Polarimeter – GAP – aboard the Solar Powered Sail Mission

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Abstract

We are now developing a gamma-ray burst polarimeter, named "GAP", to detect the polarization from the prompt emission of gamma-ray bursts. The GAP instrument is scheduled to launch in 2010 aboard the solar powered sail satellite – IKAROS. GAP is a small instrument with the net weight of 4.0 kg, but we will perform reliable polarimetry with the systematic uncertainty of a few % level due to the high symmetric structure and the capability of coincidence event sampling. At present, we have already completed to integrate the flight model, and we will make several environmental tests and calibrations.

1.1 Introduction

Gamma-Ray Bursts (GRBs) are the most energetic explosion in the universe. In the case of the brightest GRBs, the isotropic luminosity reaches 10^{54} erg s^{-1} during a short time duration, so the efficiency of energy release or conversion must be extremely high. A lot of physical informations about GRBs are revealed after the discovery of afterglows(1), but we have still little knowledge about their emission mechanism. Theoretically, the prompt emissions and the following afterglows are thought to be generated by the synchrotron radiation. In that case, we expect to detect a strong polarization (e.g. max 70 %) especially during the prompt gamma-ray (2; 3). There were earlier reports of measurement of GRB's polarization (4), but not conclusive. Therefore, the direct measurement of the polarization degree of the prompt emission is a key to solve their emission mechanism.

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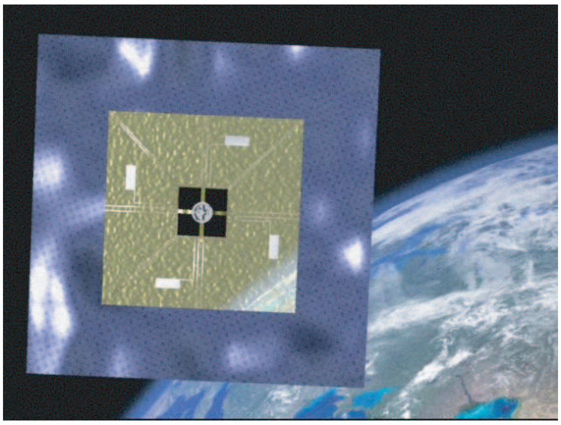

Fig. 1.1. A schematic view of the solar powered sail spacecraft – IKAROS. Expanding huge membrane of 20 m diameter, it translates the radiation pressure from the sun to the thrust of the spacecraft. (from JSPEC/JAXA Home page)

1.2 Solar Powered Sail Mission – IKAROS

The solar powered sail (5), named IKAROS, is a next Japanese engineering verification spacecraft planned to launch in 2010. Figure 1.1 is an image of the IKAROS spacecraft. Expanding the huge membrane of 20 m in diameter, it translates the radiation pressure from the sun to the thrust of the spacecraft. IKAROS will cruise toward the Venus and establish the solar-sail technology. During its cruising phase, we observe GRBs and realize an interplanetary network system to determine the direction of GRBs with a few arcmin accuracy. For the bright GRBs, we measure the polarization degree of the prompt emission of GRBs.

1.3 GAmma-ray burst Polarimeter – GAP

Figure 1.2 (left) is a schematic view of the GAP instrument (6). The detection principle is the angular anisotropy of Compton scattering for the electric field vector of the gamma-ray photon. A large plastic scintillator with a Super Bialkali type of photo-multiplier tube (PMT) is attached at the center, and 12 Cesium Iodide (CsI) scintillators are set around it. The central plastic works as the Compton scatterer, and the angular distribution of the scattered photons with coincidence are measured by surrounding CsI scintillators. This simple structure and the geometrical symmetry make us to avoid a fake modulation. Even if the GRBs come from off-axis direction, we may enable to estimate the asymmetry effect with the Monte Carlo simulations. Several fundamental capabilities are listed in table 1.1.

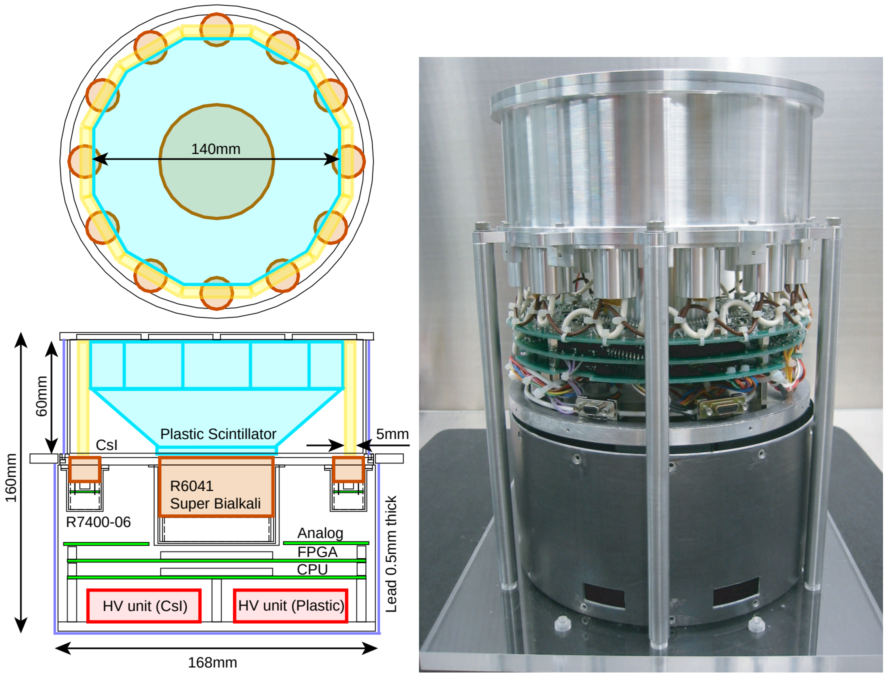

Fig. 1.2. A schematic view of GAP (left) and a whole integrated system (right).

The low-energy threshold of the plastic scintillator should be set as low as possible to measure the coincidence events correctly. According to current experiments, we can set it as $E \sim 4$ keV. Therefore we can say the energy range of polarimetry is $E > 50$ keV for 90 degree scattered events.

GAP will observe the direction of 45 degree off-axis from the anti-direction of the Sun. The instrument body, except for the detector surface, is protected by thin lead with 0.5 mm thickness for the purpose of shielding the cosmic X-ray background, low-energy cosmic-rays †, and the gamma-ray solar-flares ‡.

We have already completed the whole integration of GAP flight model in April, 2009. The total weight is very light, 4.0 kg including the electronics and high voltage modules. Until July 2009, we will perform several environmental tests like a vibration test for the HII-A locket launching, temperature cycle tests, vacuum tests, and detail software checks. We have already completed these kinds of tests using the prototype model, and their statuses were

† IKAROS is the interplanetary spacecraft, so the cosmic-rays environment is severe.
‡ The period of 2010–2012 will be a maximum of solar activities, so we must avoid the huge number of solar flares.

Table 1.1. *GAP characteristics*

Effective Area	geometry	176 cm^2
	polarization	34 cm^2 @ 100 keV
Energy Range	lightcurve	10–300 keV
	spectrum	10–300 keV
	polarization	50–300 keV
Time Resolution	lightcurve	125 msec
	spectrum	—
	polarization	1 sec
Field of View	effective	π str

pretty good. After July 2009, GAP will install on the IKAROS spacecraft, and we will perform whole integration tests.

1.4 Experiments with Highly Polarized X-ray

Hereafter we show the experimental results with the prototype GAP. Using highly polarized X-ray at synchrotron facility of KEK photon factory, we estimate the GAP's performance for the polarized X-ray. Figure 1.3(left) shows the setup of experiment. The monochromatic X-ray with 80 keV and 82 % polarization degree comes from left to right. The beam size is about 0.8×0.8 mm, so we could only perform the pencil beam experiments at KEK. The uniform irradiation for the entire surface can be operated in our laboratory using an X-ray generator which has about 15 % polarization degree and the continuum spectrum up to 100 keV.

Figure 1.3(right) shows an example of modulation curve irradiated at the center of GAP. Each data points are the coincidence events scattered from the central plastic, and the red line is the best-fit function. From this experiment, we estimate the modulation factor of 0.446 for the pencil beam. On the other hand, using the EGS5/GEANT4 simulator, we succeeded in reproducing the experimental result within the uncertainty of 2 % level.

Our GAP instrument has a wide field of view, and most of all GRBs come from diagonal off-axis direction. So we estimate the detector response for the diagonal irradiation with the pencil beam. Comparing the experiments and simulations, we can say that the both results qualitatively describe each other. But we have not conclude the detail results. We recognize the systematic uncertainty is extremely important for the polarimetry. We should make efforts to constrain the systematic uncertainty for various cases.

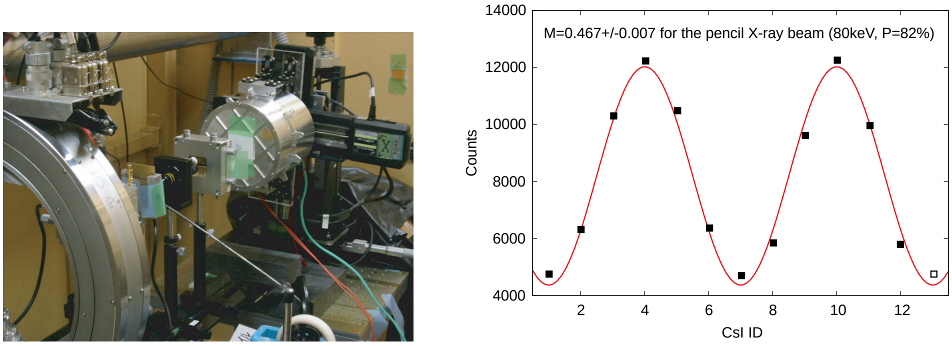

Fig. 1.3. Experiment with the synchrotron facility at KEK (left). The monochromatic 80 keV X-ray beam had the polarization degree of 82 % and a beam spread width was about 0.8 mm. An example of modulation curve irradiated at the center of GAP.

1.5 Detectability

1.5.1 Gamma-Ray Bursts and Soft Gamma-ray Repeater

In the previous section, we showed the EGS5/GEANT4 simulations could represent the experimental results with the systematic uncertainty of about 2 % level. Therefore, we consider the simulations can be adopted for various cases (energy, polarization degree, irradiation direction, etc.), and we estimate the GAP's basic capability. In figure 1.4 (left), we show the modulation factor and the efficiency for the uniform irradiation case estimated by EGS5 simulator. The GAP capability is optimized around 100 keV which generally corresponds to the energy at the maximum flux of νF_{ν} spectra. The efficiency is 0.22 and the modulation factor is 0.24, respectively.

According to the large amount of BATSE database, we estimate an expectation rate to detect positive polarization from GRBs. In figure 1.4 (right), we show the expectation rate as a function of a minimum detectable polarization which is equivalent to the GRB's polarization degree. The black line is the event rate in the entire field of view, and the red line is the one within 30 degree from optical axis. If GRBs have 70 % of polarization degree, we will detect about 4 events/year. The case of 30 % of polarization degree, we may detect from only one event with the significance of 3 σ confidence level. This expectation rate is very small, but we will be able to measure the polarization degree with the quite low systematic uncertainty, about 2 %, because of the GAP's geometric symmetry. Moreover, if the giant flare from Soft Gamma-ray Repeater is detected, we can perform the polarization measurement as well as GRBs.

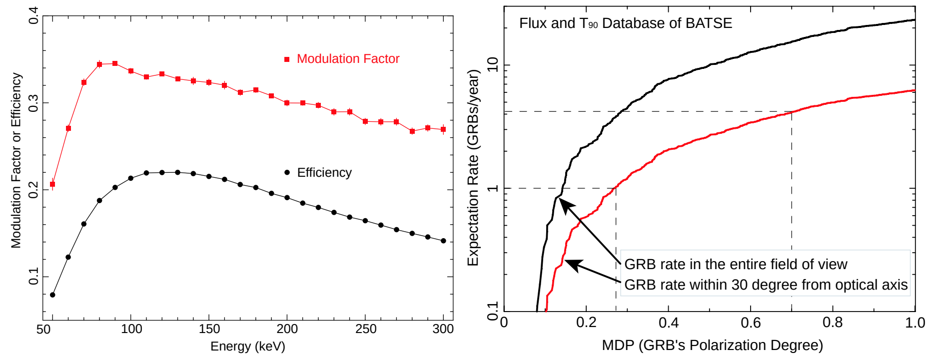

Fig. 1.4. The energy dependence of the modulation factor and the efficiency (left), and the minimum detectable polarization for GRBs based on the BATSE database.

1.5.2 Crab Nebula

We are planing to observe the Crab nebula while it locates in front of GAP instrument. Assuming the flux of Crab nebula and one of cosmic X-ray background, as the optimistic estimation, we may detect 20 % polarization with 2 days exposure time. Even if the case of 3 times higher background rate and 10 degrees of off-axis location, we may obtain a modulation with 3 σ significance by 10 days exposure time. This observation also works as the calibration of our system.

1.6 summary

(i) We will install the GRB Polarimeter GAP on the solar powered sail spacecraft which will launch in 2010.
(ii) We completed the integration of the flight model of GAP.
(iii) We will perform reliable polarimetry for GRBs, bright magnetar flares and Crab nebula with the systematic uncertainty of a few % level.
(iv) We require information about the GRB direction while we will contribute the interplanetary network system.
We are grateful if other teams would determine the GRB direction.

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