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Study of emission mechanism of Gamma-Ray Bursts by the gamma-ray polarization with IKAROS-GAP

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We report the polarization measurement in prompt γ-ray emission of GRB 100826A, GRB 110301A and GRB 110721A with the Gamma-Ray Burst Polarimeter (GAP) aboard the small solar power sail demonstrator IKAROS. We detected the firm change of polarization angle (PA) during the prompt emission of GRB 100826A with 99.9 % (3.5 σ) confidence level, and the average polarization degree (Π) of 27 ± 11 % with 99.4 % (2.9 σ) confidence level. For the later two events, we detected the strong polarization of $\Pi = 70 \pm 22$ % and $\Pi = 84^{+16}_{-28}$ % with the statistical significance of 3.7 σ and 3.3 σ, respectively. Here the quoted errors are given at 1 σ confidence level for two parameters of interest. We conclude the linear gamma-ray polarization exists in the prompt GRBs from GAP observations. The non-axisymmetric (e.g., patchy) structures of the magnetic fields and/or brightness inside the relativistic jet are therefore required within the observable angular scale of $\sim \Gamma^{-1}$. Our observation strongly indicates that the polarization measurement is a powerful tool to constrain the GRB production mechanism, and more theoretical works are needed to discuss the data in more details.

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1. Introduction

Gamma-ray bursts (GRBs) are the most energetic explosions in the universe. Since the discovery of X-ray afterglow of GRBs by BeppoSAX [1] and the identification of optical counterparts at cosmological distance, many observational facts and theoretical works have led us to understand the nature of GRBs. However, a crucial issue still remaining to answer is how to release such a huge energy as γ-ray photons in short time duration. In spite of extensive discussions with the spectral and lightcurve information being collected, there are still several possible models of GRBs [2]. Therefore the polarimetric observations provide us completely different information. If the emission mechanism is really synchrotron radiation assumed in the fireball model, the gamma-ray photons should be strongly polarized. A firm detection of linear polarization of γ-ray photons will further constrain the emission models [3, 4].

There are controversies on polarization detections in the prompt γ-ray emission of GRBs. The first report was the detection of a high linear polarization of $\Pi = 80 \pm 20$ % at a confidence level of $> 5.7\ \sigma$ by RHESSI from GRB 021206 [5]. However, reanalyzing the same data, [6] failed to confirm results of [5], and concluded that the polarization of GRB 021206 is consistent with 0 %. [7] independently checked their analyses and found a polarization value of 41^{+57}_{-44} % which is different from the previous two reports but consistent with all levels of polarization. The second reports showed also high degree of polarization for GRB 041219A with $\Pi = 98 \pm 33$ % [8] and $\Pi = 63^{+31}_{-30}$ % [9] for the brightest pulse in the 100–350 keV energy band of INTEGRAL-SPI at $2\ \sigma$ confidence level for 2 parameters of interest (Π and PA). [10] also reported the detection of polarization for time resolved analyses[1], and suggested possible variable polarization properties for the same GRB 041219A in the 200–800 keV energy band observed with INTEGRAL-IBIS. However, [10] set a strict upper limit of $\Pi < 4$ % for the same brightest pulse showing high Π in the INTEGRAL-SPI data [8, 9]. These inconsistent results between SPI and IBIS led to confusion again, and the existence of γ-ray polarization is still in debate. As the authors themselves pointed out in their reports, these results are with low statistics of $\sim 2\ \sigma$ level, and may be strongly affected by the instrumental systematics uncertainties [8, 9, 10]. These controversies and conflicts indicate difficulties in detecting the γ-ray polarization, and further observations with a reliable polarimeter are required.

2. Gamma-Ray Burst Polarimeter – GAP

IKAROS [11, 12] (Interplanetary Kite-craft Accelerated by Radiation Of the Sun) is a small solar-power-sail demonstrator and was successfully launched on 21 May 2010. IKAROS has a large polyimide membrane of 20 m in diameter, and this translates the solar radiation pressure to the thrust of the spacecraft. Since the deployment of the sail on 9 June 2010, IKAROS started the solar-sailing toward Venus.

The Gamma-Ray Burst Polarimeter (GAP) [13, 14, 15] aboard IKAROS is fully designed to measure a degree of linear polarization in the prompt emission of GRBs in the energy range of 70–300 keV. In Fig. 1 (left), we show a schematic view of the GAP instrument. The detection principle is the angular anisotropy of Compton scattering for the polarization vector. A large plastic

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[1] One should note that their definition of confidence level is given for one parameter of interest.

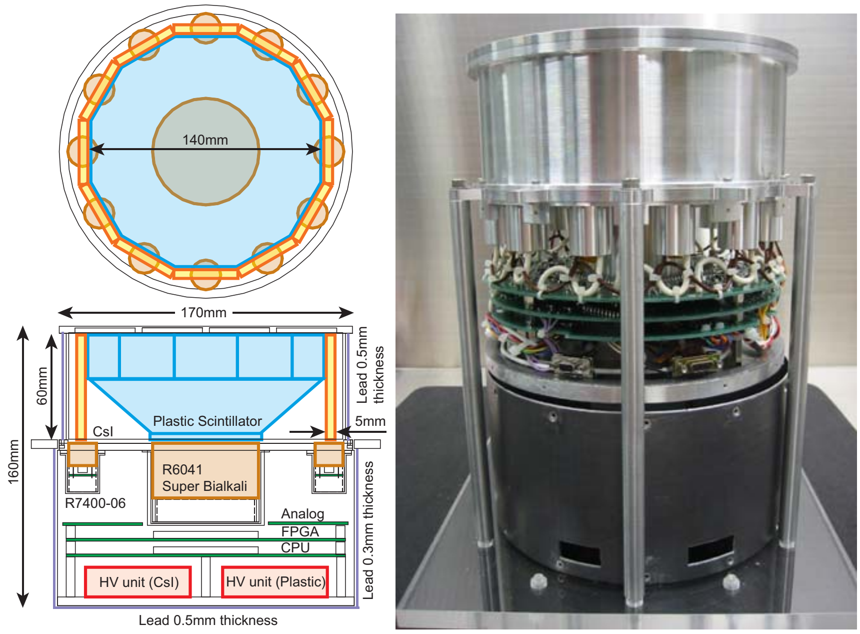

Figure 1: Left: Schematic view of the GAP sensor. A large plastic scintillator is attached at the center, and 12 CsI scintillators are set around it. Right: The photo of GAP whose lead shield is opened.

scintillator is put at the center, and 12 CsI scintillators are set around it. The central plastic works as the Compton scattering body, and the angular distribution of coincidence scattered photons are measured by surrounding CsI scintillators. If the gamma-rays are linearly polarized, the distribution of scattered photons is due to Klein-Nishina effect which approximately shows $\sin^2 \phi$ curves, where ϕ is the scattering angle. Fig. 1 (right) is a photo of the flight model of GAP.

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. Even if so, we have to estimate the systematics mainly caused by imperfect tunings of parameters in the ground and in-orbit calibrations for the off-axis radiation. First, using the proto-flight model of GAP, we performed some experiments using the radio isotopes, and measured the modulation curves for the non-polarized gamma-rays. After that, we simulated the detector response for non-polarized gamma-rays with Geant 4 simulators which is frequently used in the high-energy physics. Comparing the experimental and simulated modulation curves, we estimated the systematic uncertainty is about 1.7 % of the total coincidence gamma-rays.

3. Data Analyses

The GAP detected GRB 100826A on 26 August 2010 at 22:57:20.8 (UT). This is a very bright event with the energy fluence of 3×10^{-4} erg cm^2, and the lightcurve of the prompt emission is shown in Fig. 2 (left). First of all, we performed the polarization analysis for the entire dataset, but we set only upper limit of $\Pi < 30$ % (2 σ confidence level). Therefore we divided the entire data into two time intervals as labeled Interval-1 and -2 in a lightcurve of Fig. 2 (left). Although the

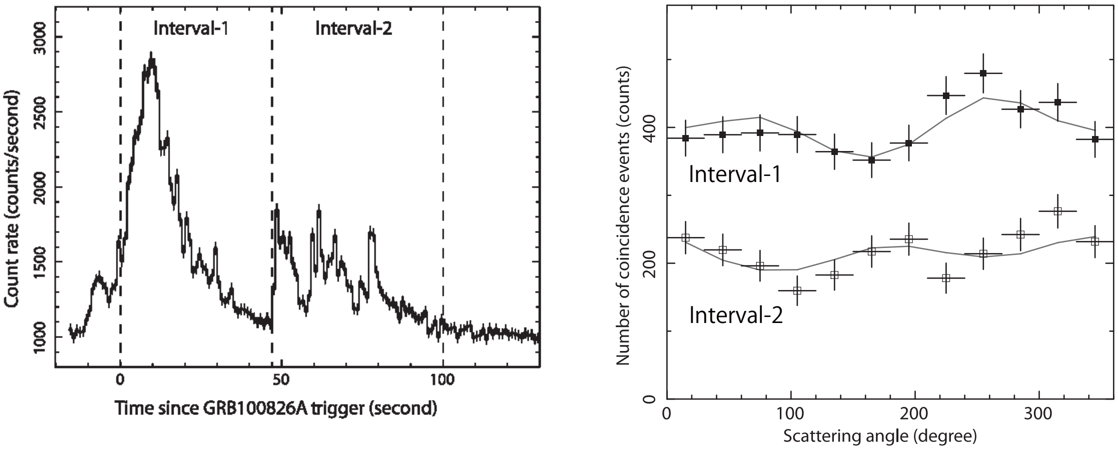

Figure 2: Left: The lightcurve of GRB 100826A. We performed time resolved polarization analyses for two time intervals. Right: The modulation curve of each interval shown in the right panel. The gray solid lines are the best fit model for each interval.

Interval-2 has several spikes, we combined all of them to keep photon statistics. We investigated the polarization degrees, Π, and the polarization angle (ϕ_p) separately for Interval-1 and -2.

The observed modulation curve is shown in Fig. 2 (right). The response of GAP for irradiation from 20.0 degree off-axis is modeled by the Monte-Carlo method with Geant 4 simulator. The gray solid lines in Fig. 2 (right) are the best-fit functions for Interval-1 and -2. The best values are $\Pi_1 = 25 \pm 15$ % with $\phi_{p1} = 159 \pm 18$ degrees for Interval-1 and $\Pi_2 = 31 \pm 21$ % with $\phi_{p2} = 75 \pm 20$ degrees for Interval-2, respectively. Hereafter the quoted errors are 1 σ confidence for two parameters of interest. The significance of polarization detection is rather low of 95.4 % and 89.0 % for Interval-1 and -2, while the difference of polarization angles is significant with 99.9 % (3.5 σ) level.

In the next step, we performed a combined fit for the two intervals, assuming that the polarization degree for Interval-2 is the same as that for Interval-1. This means that we treat Π as one free parameter to improve the statistics with the reduction of model parameters. Here the two polarization angles were still free parameters for both intervals, because the change of angle is apparent. The best-fit polarization degree is $\Pi = 27 \pm 11$ % with $\chi^2 = 21.8$ for 19 degrees of freedom. The significance of detection of polarization is 99.4 % (2.9 σ) confidence level. These results are summarized in [16].

We also detected the significant polarization from GRB 110301A and GRB 110721A, whose time durations are much shorter than the one of GRB 100826A. We analyzed these two data, and detected the polarization degree of $\Pi = 70 + / - 22$ % for GRB110301A, and $\Pi = 84^{+16}_{-28}$ % for GRB110721A. The confidence level is 3.7 σ and 3.3 σ, respectively. We performed time resolved polarization analyses for each data. However the polarization angle did not change during the prompt emission within the error of 11 degrees.

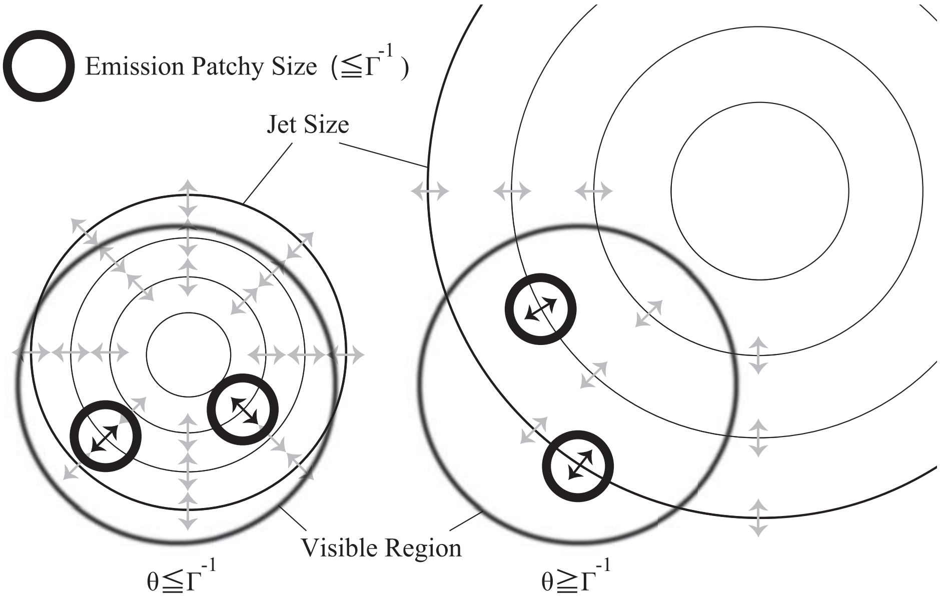

Figure 3: An example of polarization map (gray vectors) on the jet surface for the toroidal magnetic fields. Left: The case of $\theta \leq \Gamma^{-1}$. Any patches of different polarization angle can be observed, so the rapid change of polarization angle can be explained. Right: The case of $\theta \geq \Gamma^{-1}$. We can observe only small fraction of jet surface, so it is difficult to detect the strong change of polarization angle.

4. Discussion

We discussed several emission model in [16]. When we assume the helical magnetic fields to drive the relativistic jet, we expect the toroidal magnetic fields on the jet surface. Then the distribution of polarization is shown in Fig. 3. We can observe only the small fraction of the jet because of the relativistic beaming effect. When we observe GRBs on the jet axis, the net polarization is disappeared to be zero. However in the case of slightly off-axis observation, the net polarization is remaining. Moreover, if the emission regions are patchy structures with the scale of $\leq \Gamma^{-1}$, we expect the rapid change of the polarization angle for the case of $\theta \leq \Gamma^{-1}$ (Fig. 3 left). On the other hand, for the case of $\theta \geq \Gamma^{-1}$ as shown in Fig. 3 (right), the strong changes of polarization angle are not expected while the polarization exists.

For the case of globally random but locally coherent magnetic fields, e.g. the shock turbulence on the jet surface, we can also explain both the existence of polarization and the change of polarization angle when we assume the patchy structures. However, if the gamma-rays are uniformly emitted from the jet surface (i.e. the uniform jet, the axisymmetric jet), it is difficult to explain the rapid change of polarization angles. Therefore we suggest that the inner structures exist in the relativistic jet. Although we cannot exclude the photospheric (e.g. [17]) and the Comptonized emission model only from these observations, one should assume the special conditions to explain the gamma-ray polarization.

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5. Questions and Answers

1. Q. How large is the absolute value of magnetic fields?
   A. The absolute strength of magnetic fields can not be estimated only by the polarization. If the emission mechanism is the synchrotron radiation, the observed $E_{peak} = 600$ keV is equivalent to the magnetic fields of $B = 10^3 \sim 10^4$ G.

2. Q. The spectral parameters vary in the prompt emission. How do you deal with?
   A. We considered the effects when we calculated the detector response with Geant 4.

3. Q. Is there any systematics due to the attitude of spacecraft in time?
   A. The spin axis of IKAROS is stable, and it does not affect the observed modulations.

4. Q. Can the magnetic reconnection explain the observed results?
   A. It is difficult to answer because I have no idea about the coherent scale (size) of magnetic field for the magnetic reconnection. For example, the micro scale of magnetic field generated by the Weibel instability can not explain the observed polarization.