DETECTION OF GAMMA-RAY POLARIZATION IN PROMPT EMISSION OF GRB 100826A

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ABSTRACT

We report the polarization measurement in prompt γ-ray emission of GRB 100826A with the Gamma-Ray Burst Polarimeter on board the small solar-power-sail demonstrator IKAROS. We detected the firm change of polarization angle (PA) during the prompt emission with 99.9% (3.5σ) confidence level, and the average polarization degree (Π) of 27% ± 11% with 99.4% (2.9σ) confidence level. Here the quoted errors are given at 1σ confidence level for the two parameters of interest. The systematic errors have been carefully included in this analysis, unlike other previous reports. Such a high Π can be obtained in several emission models of gamma-ray bursts (GRBs), including synchrotron and photospheric models. However, it is difficult to explain the observed significant change of PA within the framework of axisymmetric jet as considered in many theoretical works. 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 ∼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 detail.

Key words: gamma-ray burst: individual (GRB 100826A) – instrumentation: polarimeters – polarization – radiation mechanisms: non-thermal – relativistic processes

1. INTRODUCTION

Gamma-ray bursts (GRBs) are the most energetic explosions in the universe, and the isotropic luminosity reaches 1054 erg s⁻¹ for the brightest bursts. Since the discovery of X-ray afterglow of GRBs by BeppoSAX (Costa et al. 1997) 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 that still stands is how to release such a large energy as γ-ray photons. In spite of extensive discussions using the spectral and light curve information collected, there are still several possible models of GRBs (Mészáros 2006). The polarimetric observations provide us with completely different information. A firm detection of linear polarization of γ-ray photons will further constrain the emission models (Lazzati 2006; Toma et al. 2009).

The polarization measurement of GRBs has been performed in the late optical afterglows at first (Covino et al. 1999, 2004; Wijers et al. 1999; Rol et al. 2000; Gorosabel et al. 2004). All of these results show a polarization degree (Π) of a few percent level. Mundel et al. (2007) set an upper limit of Π < 8% for the early optical afterglow. Detailed observations are performed for the optical afterglow of GRB 030329, and time variations of the polarization degree and polarization angle (PA) were reported (Greiner et al. 2003). Recently, a polarization degree of Π = 10% ± 1% was reported for the early optical afterglow of GRB 090102, at hundreds of seconds since the burst trigger (Steele et al. 2009).

On the other hand, 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 Π = 80% ± 20% at a confidence level of >5.7σ by RHESSI from GRB 021206 (Coburn & Boggs 2003), although independent groups could not confirm any polarization signals by reanalyzing the same data (Rutledge & Fox 2004; Wigger et al. 2004). The second reports also showed high degree of polarization for GRB 041219A with Π = 98% ± 33% (Kalemci et al. 2007) and Π = 63±31% (McGlynn et al. 2007) for the brightest pulse in the 100–350 keV energy band observed with the International Gamma-Ray Astrophysics Laboratory (INTEGRAL)-Space Platform Interferometry (SPI) at 2σ confidence level for two parameters of interest (Π and PA). Götz et al. (2009) also reported more significant detection for time-resolved analyses and suggested possible variable polarization properties for the same GRB 041219A in the 200–800 keV energy band observed with INTEGRAL-IBIS. However, Götz et al. (2009) set a strict upper limit of Π < 4% for the same brightest pulse showing high Π in the INTEGRAL-SPI data (Kalemci et al. 2007; McGlynn et al. 2007). (Götz et al. 2009 explained that the null net polarization degree results from the superposition of signals with different PAs. However, this interpretation cannot explain the positive detection by INTEGRAL-SPI simultaneously.) These inconsistent results between SPI and IBIS has 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 ~2σ level and may be strongly affected by the instrumental systematics uncertainties (Kalemci et al. 2007; McGlynn et al. 2007; Götz et al. 2009). These controversies and conflicts indicate difficulties in detecting the γ-ray polarization.

In this Letter, we report the detection of γ-ray polarization and also the change of PA for the extremely bright GRB 100826A using the newly developed GRB polarimeter. Our polarimeter is completely designed for the polarization measurement of prompt GRBs and well calibrated during the developing phase before launch. Specifically, using a detector of proto-flight model, we experimentally and numerically understand the response for polarized γ-rays with low systematic uncertainties. In the following sections, we show the observation (Section 2), data analysis (Section 3), and discussion of the emission mechanism of prompt GRBs (Section 4).

2. OBSERVATIONS

The Interplanetary Kite-craft Accelerated by Radiation Of the Sun (IKAROS; Kawaguchi et al. 2008; Morie et al. 2009) is a small solar-power-sail demonstrator that was successfully launched on 2010 May 21. IKAROS has a large polyimide membrane 20 m in diameter, which translates the solar radiation pressure into the thrust of the spacecraft. Since the deployment of the sail on 2010 June 9, IKAROS has started solar-sailing toward Venus.

The Gamma-Ray Burst Polarimeter (GAP; Yonetoku et al. 2006, 2011; Murakami et al. 2010) on board IKAROS is fully designed to measure the degree of linear polarization in the prompt emission of GRBs in the energy range of 70–300 keV. The detection principle is the anisotropy of Compton scattered photons. If the incident γ-rays are linearly polarized, the distribution of scattered photons is due to the Klein–Nishina effect which approximately shows sin² φ curves, where φ is the scattering angle.

The GAP consists of a central plastic scatterer 17 cm in diameter and 6 cm in thickness, and the surrounding 12 CsI(Tl) scintillators 5 mm in thickness. The coincidence events within a gate time of 5μs between the signal from any CsI and that from the plastic are accepted for polarization analysis. The GAP’s high axial symmetry in shape and the high gain uniformity are key to reliable measurement of polarizations, and to avoid a fake modulation due to background γ-rays. There are no external parts of the spacecraft inside the GAP field of view. Moreover, the detector cases (chassis), except for the detector top, are covered by thin lead sheets with 0.5 mm thickness. Therefore, the effects of background γ-rays scattered by the spacecraft body are negligible.

The GAP detected GRB 100826A on 2010 August 26 at 22:57:20.8 (UT) on the way to Venus at about 0.21 AU away from the Earth. The light curve of the prompt emission is shown in Figure 1. This burst was also detected by several satellites and was localized by an interplanetary network (IPN; Hurley et al. 2010). Combining the GAP data with the published IPN information, the direction of this burst is derived as (α, β) = (279.6 ± 0.2, −22.3 ± 0.5), which corresponds to 20.0 deg off-axis from the center of the GAP field of view. An energy fluence of this burst is (3.0 ± 0.3) × 10⁻⁴ erg cm⁻² in the 20 keV–10 MeV band by KONUS (Golenetskii et al. 2010), which is the top 1% of the brightest events listed in the BATSE catalog. The low- and high-energy photon indices are reported as αB = −1.31±0.06 and βB = −2.1±0.1, respectively, and the νFν peak energy as Eν = 606±139 keV (Golenetskii et al. 2010). An optical afterglow of this GRB was not reported, so its redshift is unknown.

3. DATA ANALYSIS

We divided the entire data into two time intervals, labeled Interval-1 and -2 in the light curve in Figure 1. The total numbers of γ-rays photons after subtracting the background are 32,924 and 19,007 photons for each interval, respectively. The first part of this burst shows a large flare lasting 47 s since the trigger, and the following 53 s consists of multiple spikes. Although Interval-2 has several spikes, we combined all of them to keep photon statistics.

We used the background modulation curve obtained by the 36.7 hr integration just before and after the GRB trigger time.
In this case, the averaged coincidence background rate is quite stable at 5.6 counts s\(^{-1}\) CsI\(^{-1}\), and its modulation curve can be described as constant with the standard deviation at 0.1% level. After subtracting the background modulation, the total numbers of the coincidence \(\gamma\)-rays (polarization signals) are 4,821 and 2,733 for Interval-1 and -2, respectively.

### 3.1. Model Functions

When we perform the polarization analysis, we calculated the model function (or the detector response) for the polarized gamma-rays with the Geant 4 Monte Carlo simulator. A geometrical mass model of GAP was introduced in Yonetoku et al. (2011). We can set all the possible situations with different off-axis angles, azimuthal phase angles, spectral parameters, as well as polarization degrees and angles of incoming \(\gamma\)-rays. In this analysis, the free parameters are the polarization degrees and angles, since the other parameters are constrained as shown in Section 2.

Simulating the interactions between the incoming gamma-rays and the geometrical mass model with the Monte Carlo method, we created the model functions of the modulation curves. Then, we selected the coincidence events between the plastic and one CsI scintillator as the polarization signals. We simulated the model function with step resolutions of 5% for polarization degrees and 5 deg for phase angles. We will fit the observed modulation curves with the model function using a least-squares method in the following subsections.

### 3.2. Systematic Uncertainty

We should treat not only the statistical error but also the systematic uncertainties correctly. Here, the systematic uncertainties mean any unexplainable difference between the observed modulation curve and the simulated one.

Imperfect tunings of parameters in the ground and in-orbit calibrations for the incident radiation, especially from the off-axis direction, cause more important systematic uncertainty. First, we performed some ground-based experiments with non-polarized radio isotopes \(^{57}\)Co (122 keV) and \(^{241}\)Am (59.5 keV). They were set at the distance of 1.0 m from the center of the proto-flight model with several incident angles from 0 to 50 deg with the step resolutions of 5 deg. We measured experimental modulation curves for each setup. After that, on the assumption of non-polarized \(\gamma\)-rays with the monochromatic energy of 122 keV and/or 59.5 keV, we calculated the numerical modulation curve with the Geant 4 simulator.

Then, of course, the both modulation curves show some discrepancies that cannot be explained within the statistical uncertainty because of instrumental systematic uncertainties. We calculated the standard deviation of two modulations and derived the systematic errors to be \(\sigma_{\text{sys}} = 1.8\%\) of the total coincidence \(\gamma\)-rays for the case of a 20.0 deg incident angle. Although this value is not negligible, the statistical error (about \(\sigma_{\text{stat}} \sim 5\%\) levels) still dominates the systematic one in this case. We included the systematic uncertainty into the total errors as \(\sigma_{\text{total}}^2 = \sigma_{\text{stat}}^2 + \sigma_{\text{sys}}^2\) for each bin of polarization data.

### 3.3. Fitting the Polarization Data

First, we performed the polarization analysis for the whole data set of time interval 0–100 s. Then we obtained an acceptable result with the model of the non-polarized modulation curve and set only an upper limit of \(\Pi < 30\%\) (2\(\sigma\) confidence level). We consider the possibility that the polarization degree may be weak if the polarization angle changes during the entire burst duration, as suggested by Götz et al. (2009). Therefore, we performed time-resolved polarization analyses for the data sets of Interval-1 and -2. In Figure 2, we show the
and the PA (the preceeding subsection.
uncertainty but also the 1.8% systematical one as estimated in
Π are the best-fit functions for Interval-1 and -2. The best values
Carlo method with the Geant 4 simulator. The gray solid lines
irradiation from 20.0 deg off-axis is modeled using the Monte
levels of the Δχ² values. The null hypothesis (zero polarization degree) can be ruled out with 99.4% (2σ) confidence level.

Figure 3. Δχ² map of confidence contours in the (Π, φp) plane for GRB 100826A, obtained by the combined fit of the Interval-1 and -2 data. Here φp is the phase angle for Interval-1. The white dot is the best-fit result, and we calculate Δχ² values relative to this point. A color scale bar along the right side of the contour shows observed source modulation curves as a function of scattering angle for both time intervals after subtraction of background. The error bars shown in Figure 2 include not only the statistical uncertainty but also the 1.8% systematical one as estimated in the preceeding subsection.

At the first step, we investigated the polarization degrees, Π, and the PA (φp), measured counterclockwise from the north, separately for Interval-1 and -2. Then, the response of GAP for irradiation from 20.0 deg off-axis is modeled using the Monte Carlo method with the Geant 4 simulator. The gray solid lines are the best-fit functions for Interval-1 and -2. The best values are Π₁ = 25% ± 15% with φp₁ = 159 ± 18 deg for Interval-1 and Π₂ = 31% ± 21% with φp₂ = 75 ± 20 deg for Interval-2, respectively. Hereafter the quoted errors are at 1σ confidence for two parameters of interest. The significance of the polarization detection is rather low at 95.4% and 89.0% for Interval-1 and -2, while the difference of the PAs is significant at the 99.9% (3.5σ) 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 the model parameters. Here the two PAs were still free parameters for both intervals, because the change in angle is apparent. The best-fit polarization degree is Π = 27% ± 11% with χ² = 21.8 for 19 degrees of freedom. We show a Δχ² map in the (Π, φp) plane in Figure 3, where we represent φp = φp₁. The significance of detection of polarization is at the 99.4% (2.9σ) confidence level.

Gamma-ray detectors on board RHESSI and INTEGRAL have complex geometry, and the polarization analysis may be highly affected by the instrumental systematics as several other researchers have mentioned (Kalemci et al. 2007; McGlynn et al. 2007). In contrast to these, GAP is developed for the purpose of GRB polarimetry with high axial symmetry in shape. The systematic uncertainty is quantitatively estimated and found to be as small as 1.8% of the total polarization signals, as described above. Of course, GAP is well calibrated for polarized γ-rays before launch (Yonetoku et al. 2011). Therefore, for the prompt emission of GRBs, we conclude that this is probably the most convincing detection of polarization degrees and angles so far.

4. DISCUSSION

The emission mechanisms of GRBs that are being actively discussed using the spectral and light curve information collected so far includes synchrotron emission of electrons at the optically thin regions of relativistic jets and quasi-thermal emission from the photospheres of jets (for a review, see Mészáros 2006). Our reliable polarimetric observations may help further constrain the emission mechanisms as well as the structure of the emission sites and the magnetic fields. The main results of our polarimetric observation of GRB 100826A are the following: (1) the polarization degree averaged over the burst duration is Π = 27% ± 11% in the energy range of 70–300 keV below Ep ≈ 600 keV and (2) the PA significantly varies from Interval-1 to -2.

It has been theoretically shown that sizable net polarizations can be obtained both in the synchrotron and photospheric emission mechanisms. The synchrotron mechanism involves several different types of models with respect to magnetic field structure (for reviews, see Lazzati 2006; Toma et al. 2009): (a) synchrotron in a globally ordered toroidal field (SO model; Granot 2003; Lyutikov et al. 2003; Zhang & Yan 2011), (b) in random fields on plasma skin depth scales (SR model; Granot 2003; Nakar et al. 2003), and (c) in random fields on
hydrodynamic scales (SH model; Inoue et al. 2011; Gruzinov & Waxman 1999). In the SR model, the magnetic field directions are assumed to be random not isotropically but mainly in the plane perpendicular to the local expansion direction. In this case a high degree of polarization can be obtained only when the observer sees the jet slightly off-axis, i.e., \( \theta_o \sim \theta_j + \Gamma^{-1} \), where \( \theta_o \) is the angle between the line of sight and the jet axis, and \( \theta_j \) and \( \Gamma \) are the opening half angle and the bulk Lorentz factor of the jet, respectively. On the other hand, (d) in the photospheric emission model (Ph model), we also expect strongly polarized radiation when the radiation energy is comparable to or smaller than the baryon kinetic energy at the photosphere (Beloborodov 2011). Around the photosphere, the photon distribution is highly anisotropic, which can lead to high levels of polarization through the last electron scatterings (see also Eichler & Levinson 2003; Lazzati et al. 2004 for the other Comptonization models). We also need the condition \( \theta_o \sim \theta_j + \Gamma^{-1} \) in this model to have a high net polarization. The above four models can be consistent with our result (1).

Our result (2) provides us with very important information, which excludes axisymmetric jets both in the synchrotron and photospheric emission models. If the emitting surface is symmetric around the jet axis, as assumed by most authors in the SO, SR, and Ph models, the direction of the net polarization in the high \( \Pi \) case is determined to be either parallel or perpendicular to the direction from the jet axis toward the line of sight. Therefore, we conclude that the non-axisymmetric structure of the brightness and/or the magnetic fields on the observable angular scale \( \sim \Gamma^{-1} \) are required to have a substantial change of PA (see also Lazzati & Begelman 2009).

A possible solution for results (1) and (2) is patchy emission in the SO, SR, or Ph model, or a patchy magnetic field structure, i.e., the SH model. For instance, the SH model produces net polarization as \( \Pi \sim 70\%/\sqrt{N} \), where \( N \) is the number of independent patches with coherent magnetic field in the observable region. The polarization degree for \( N \sim 2-50 \) can be consistent with the individual results for Interval-1 and -2 within 1σ confidence. The angle of the averaged polarization is statistically random, so that they can be consistent with our result (2). Similar arguments may be made for the patchy SO, SR, and Ph models. In the patchy SO model, the emission from each patch can have different PAs's easily when \( \theta_j \sim \Gamma^{-1} \). In the patchy SR and Ph models, we no longer require the off-axis viewing of the jet, and the emission from each of the off-axis viewed patches has high \( \Pi \) and different PA.

How can we further constrain the models with the analysis results of other bursts detected by GAP and the future polarimetry missions? We note that the statistical analysis results of the SO, SR, and Ph models in Toma et al. (2009) are not applicable since they assume axisymmetric jets. In the Ph model, the patch scales are constrained as \( \theta_p \gtrsim \Gamma^{-1} \). Then, high local polarizations are obtained from patches with \( \theta_o \sim \theta_p + \Gamma^{-1} \gtrsim 2\Gamma^{-1} \), although their brightness is much smaller than that from patches with \( \theta_o \lesssim \Gamma^{-1} \) because of the relativistic beaming effect. Thus, it is not expected that all the bright bursts have a high net polarization in the patchy Ph model. The statistical studies of the GAP bursts might provide us with some implications for further constraining the emission mechanism.

This polarimetric observation for GRB 100826A has been performed in the energy range below \( E_p \). In reality, the spectral indices \( \alpha_p \) of bursts below \( E_p \) are not fully explained in the framework of synchrotron or photospheric mechanism. In the synchrotron mechanism, the radiative cooling of emitting electrons should not be so rapid as to produce a sufficiently hard spectrum below \( E_p \), so that the emission region could be thick, unlike the thin shell emission assumed in many papers (e.g., Asano & Terasawa 2009). The photospheric models include the idea that the emission below \( E_p \) is a superposition of many quasi-thermal components with different temperatures and/or \( \Gamma \) (e.g., Ryde et al. 2010; Toma et al. 2011). Clearly, more studies on the energy dependence of polarization (as well as the non-axisymmetric structure of the jet) in each model are needed to discuss the observational results quantitatively.

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