Development of Gamma-ray Burst Polarimeter for Multi-Platform Use

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Abstract: To clarify the radiation mechanism of gamma-ray bursts, we have been developing gamma-ray burst polarimeters using segmented plastic scintillators and multianode photomultipliers. We have three potential programs for the developed polarimeters. These are LEAP project, PolariS project, and GAP 2 project on IKAROS-II. We explain the status of development for the polarimeter and the expected performance.

Motivation

The gamma-ray burst (GRB) is the most energetic phenomena in the universe. Since the discovery in the late 1960', several thousands of GRBs have been observed. However, the radiation mechanism of the gamma rays are not clarified yet. There are two predominant theoretical models as shown in Figure.1. The one is the synchrotron radiation model and the other one is the photosphere model. According to the standard fireball model, the fireball which emerges at the central engine is accelerated to 99.999% of the light speed along the jet. Though the fireball is opaque at first, it becomes transparent as the fireball expands. Then quasi-thermal X rays can be emitted from the fireball. They can be observed as gamma rays from the observer on the earth because the ejecta moves very fast. The photosphere model is a quasi-thermal process that does not produce strongly polarized photons, except for a special case. As the fireball expands more and more, the faster ejecta collides with the slower one. So the internal shock occurs and then electrons are thermalized. The electrons emit X rays by synchrotron radiation with magnetic fields. They can be observed as gamma rays from the observer on the earth. In the case of the synchrotron model, if the magnetic field is ordered, it can have strong polarization as much as 40%. So the observation of the polarization can clarify which theoretical model is correct.

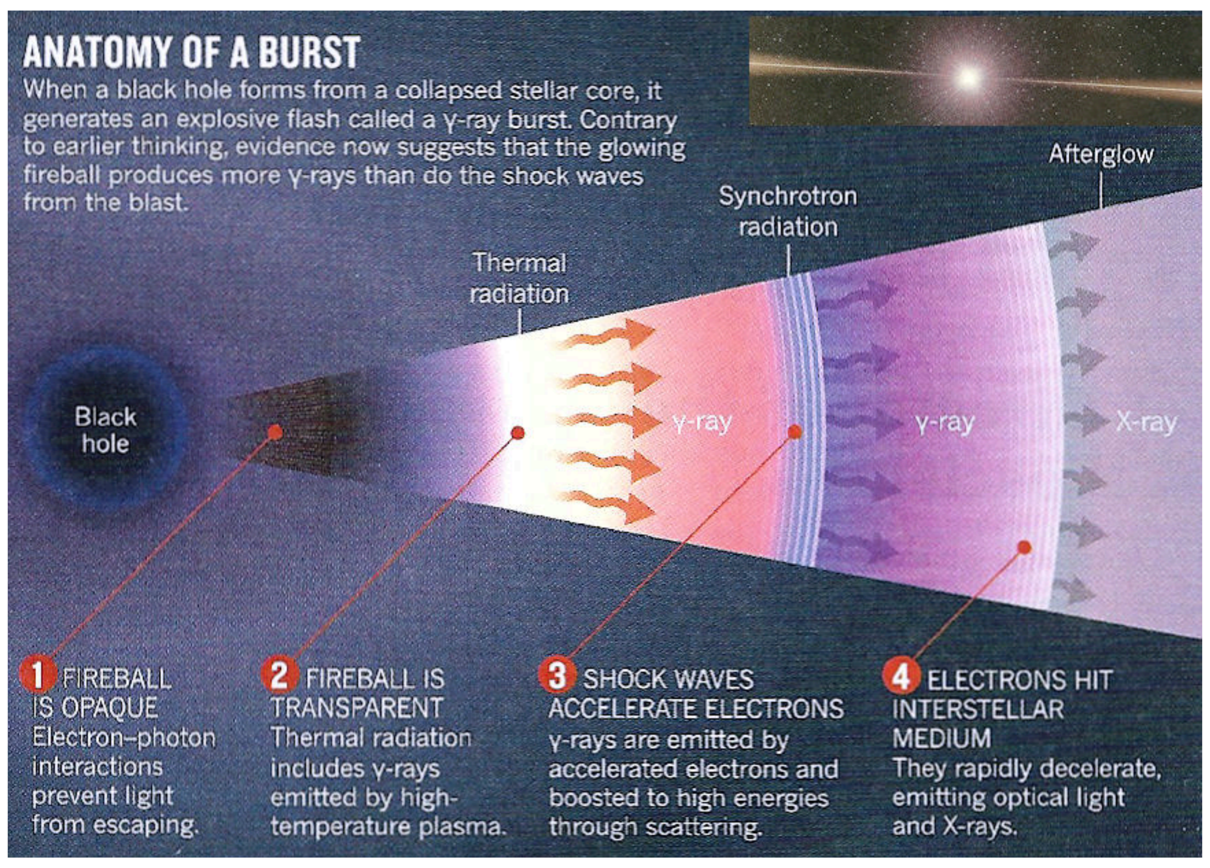


Figure.1 (http://universe-review.ca/I08-08-GRB.jpg)

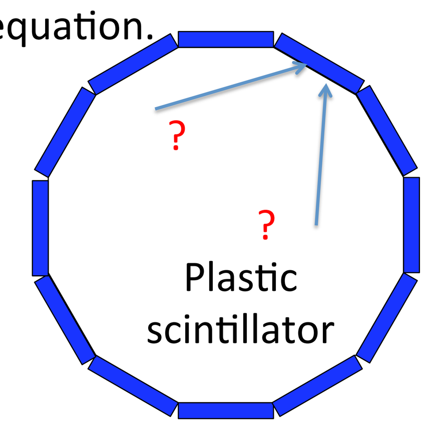
GAmma-ray burst Polarimeter (GAP) was launched in 2010 to be installed in IKAROS solar sale demonstrator. Though the weight was only 3.8 kg, it was specifically designed to measure the polarization. In one year, the GAP measured polarization for three GRBs. Because strong polarization is observed for two GRBs of the three, the synchrotron model with ordered magnetic fields is sustained from the results. However, because the effective area was small, too few GRBs were observed. Mission with large effective area is desirable.

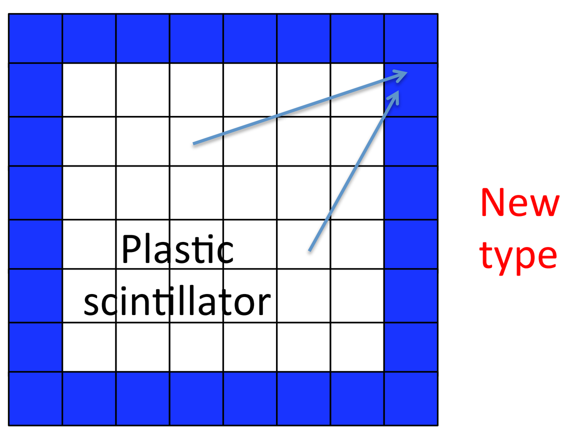
Design Concept

We have been developing Compton-scattering-type polarimeters. Because the azimuthal scattering angle φ depends on the polarization vector of the incident gamma rays, the information on the polarization of the incident gamma rays can be obtained by measuring the two dimensional scattering direction as shown in the following equation.

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

r_0 : classical radius of an electron
θ : scattering angle for the incident gamma ray
φ : azimuthal scattering angle for the electric vector of the incident gamma ray
k_0 : the energy for the incident gamma ray
k : the energy for the scattered gamma ray





For this type of polarimeter, it is very important to read out the scattering and absorption positions for the determination of the polarization vector. However, the GAP can only detect rough absorption position. So we adopt the modestly segmented scatterer for the next generation polarimeters. Multianode photomultipliers and plastic scintillators are used as the segmented scatterer.
As the size of the scatterer is small, the light collection efficiency goes up. So the sensitivity for low energy goes up.

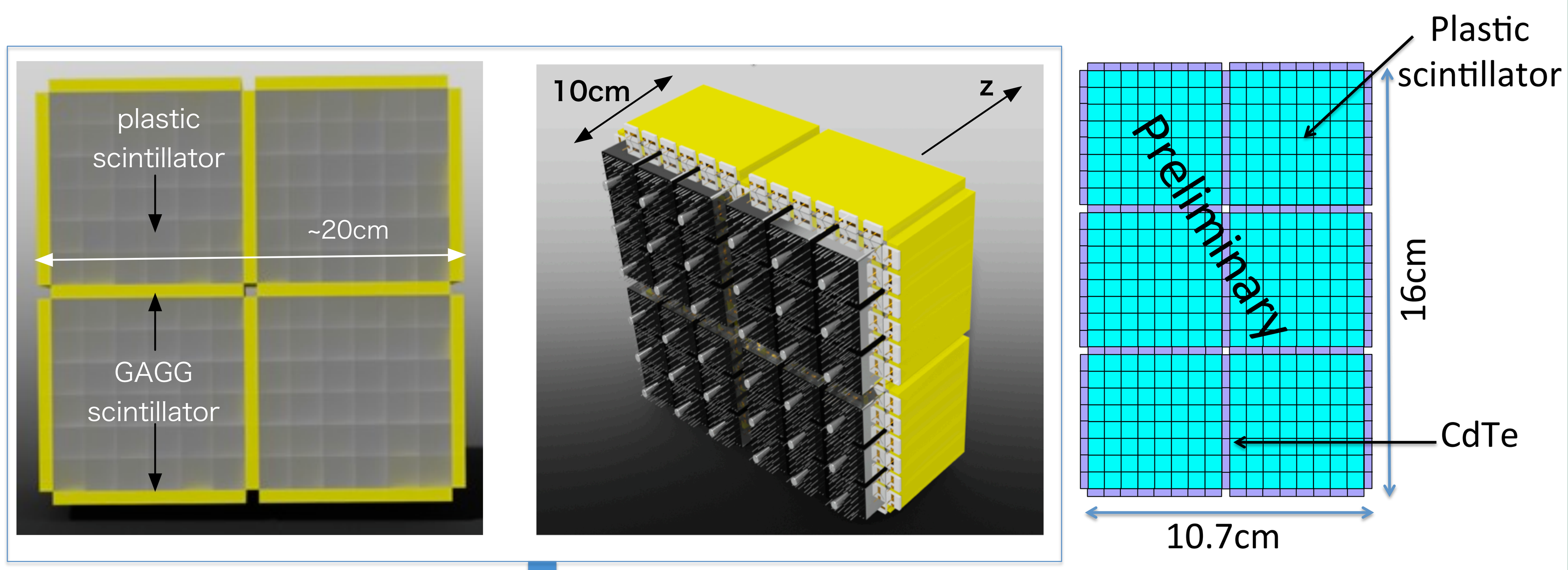
Strategy

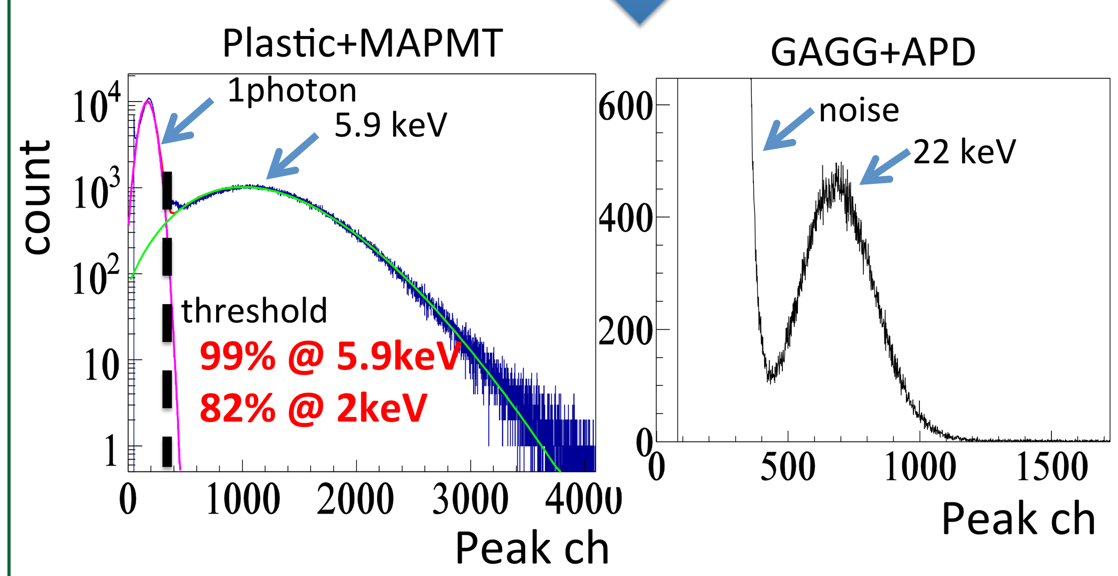
There are three potential applications of our polarimeters.

1)LEAP (Large Effective Area Polarimeter for gamma-ray bursts)
We will submit the proposal on 2016 and it will be launched to the ISS on 2022 if it will be adopted. The geometrical area will be 4800 cm^2.
2)PolariS (Polarimetry Satellite)
In the case that a polarimetry satellite will not be adopted for the next U.S. SMEX program, we will plan to submit the proposal for Japanese small satellite program. It will be decided in 2017. The geometrical area will be 1200 cm^2.
3)GAP2 (GAmma-ray burst Polarimeter 2) on IKAROS-II
The proposal for the IKAROS-II will be submitted in 2015. If it will be adopted, it will be launched In 2021. The geometrical area will be 162 cm^2 because of the strict weight limit .

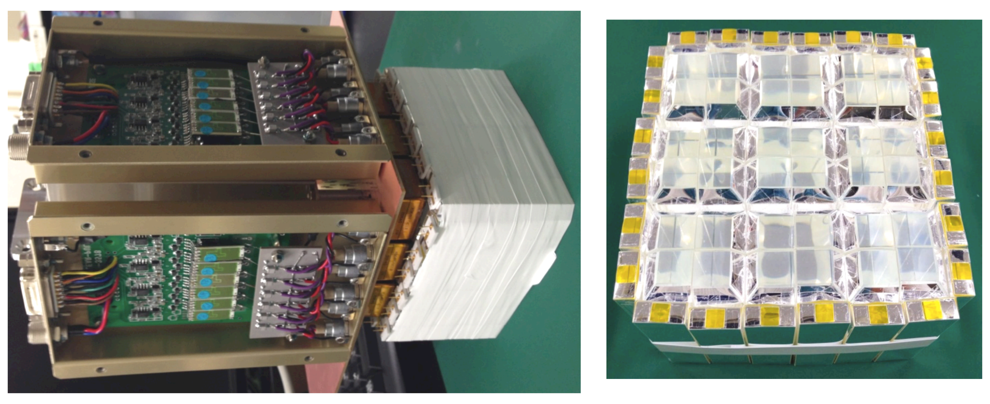
Design of Polarimeter

In the left and central figures, the schematic views of the polarimeter for the LEAP project and the PolariS project are shown. It consists of segmented 144 plastic sicntillators (14.5×14.5×60mm^3) as scatterers and segmented 72 GAGG scintillators (14.5×6×60mm^3) as absorbers. Each signal is read out by 36 MAPMT (R11265-200-M16) and 72 APD (S8664-55). The GAGG scintillator is a new comer with good performance. It has high light yields of ~55000 photons/MeV and high density of 6.63g/cm^3. 16 modules will be installed for the LEAP project. 4 modules will be installed for the PolariS project.
In the right figure, the schematic view of the GAP2 is shown. It consists of segmented 384 plastic scintillators (6.5×6.5×30mm^3) as scatterer and 136 CdTe (6.5×1.0×30mm^3) as absorber.
Because the strict weight limit is required, it is designed as less than 5 kg. It is tentative design, yet.



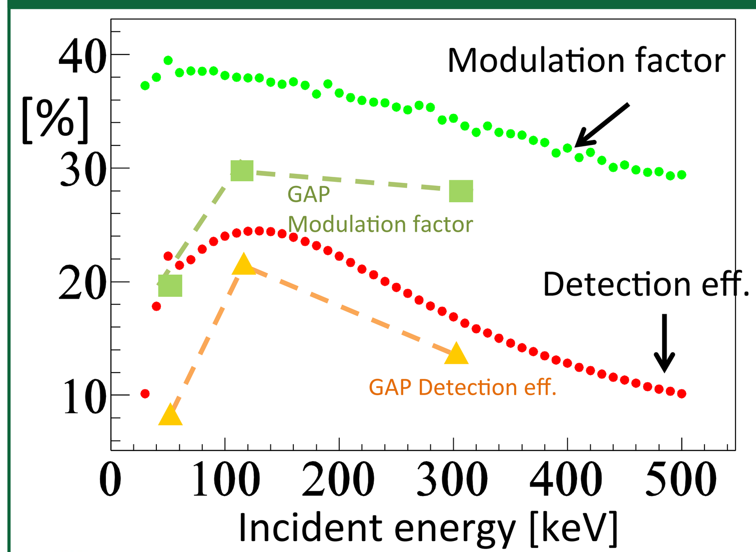


The left and right figures corresponds to pulse height spectrum for irradiation of plastic scintillator with 5.9 keV X rays and that of GAGG with 22 keV X rays, respectively.
From these data, it is recognized that even 30 keV gamma rays can be detected.

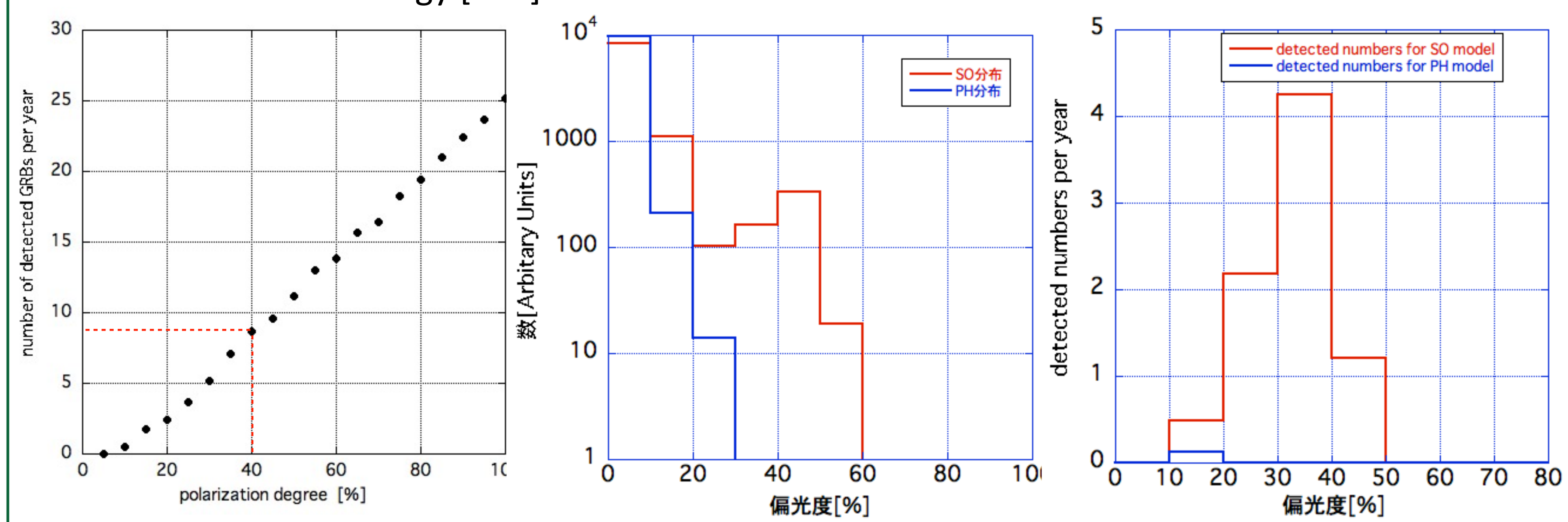


The left and right pictures show bread board model of ¼ size and the bundle of scintillator, respectively. The final circuit will be completed in February 2015.
In Oct. 2015, the new prototype polarimeter will be manufactured and tested in MSFC/NASA.

Expected Performance



From basic experiments and computer simulation, we estimated the detection efficiency and the modulation factor for each energy. Though the GAP is not sensitive at 30 keV, our new polarimeter has the detection efficiency of 10% at 30 keV. Moreover, it has detection efficiency of 10 % even at 500 keV due to the use of GAGG. On the other hand, the modulation factor of the new type is 1.5 times higher than that of the GAP in every energy.



The left figure shows the number of GRBs polarization of which can be detected per year. If the gamma rays are more than 40 % polarized, the polarization of 8 or 9 GRBs can be detected per year for one module. Because the LEAP and the PolariS will have 16 and 4 modules, respectively, the polarization for about 130 GRBs and 35 GRBs will be detected for the LEAP and the PolariS, respectively. The central figure shows the polarization distribution for the synchrotron model with ordered magnetic fields (SO model) and the photosphere model (PH model). As shown in this figure, the degree of polarization is higher for the SO model than for the PH model. The right figure shows the distribution the polarization of which is detected by our new polarimeter. It corresponds to one module per year. If the SO model is plausible, one module can detect polarization for about 8 GRBs. However if the PH model is plausible, strong polarization can not be observed. So we can understand which is plausible.

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