UNISEC Space Takumi Journal for Practical Study of Problem Finding and Solving in Space Systems
UNISEC Space Takumi J. Vol.1, No.2, pp.1-6, 2011
Published online 1 July 2011 in Space Takumi Online Library (http://space-takumi.unisec.jp)

ガンマ線バーストと X 線突発天体の監視による重力波天文学の設立

米徳　大輔 [1,*,†], 若島　雄大 [1], 米持　元 [1], 高田　俊介 [1], 瀬田　大樹 [1], 吉田　和輝 [1],
鳥屋子　あすか [1], 池田　博一 [2]

[1] 金沢大学　理工研究域　数物化学系,
〒920-1192　石川県　金沢市　角間町
[2] 宇宙科学研究所,
〒252-5210　神奈川県　相模原市　中央区　由野台　3-1-1

概要
現在、建設中の重力波観測施設(KAGRA, Advanced LIGO, VIRGO)において、中性子星連星の合体は、重力波検出の最有力な候補天体である。このとき、短時間のガンマ線バーストを発生すると考えられており、重力波と同時に大量のX線・ガンマ線を放射する。もし、超小型衛星に搭載したX線撮像検出器によって全天監視を実現できたなら、重力波天文学という新分野の創設に大きく貢献できるだろう。金沢大学では 2014 年度より先端宇宙理工学教育プログラムを開設する。2018-19 年の打ち上げを目指して 50kg 級の人工衛星を開発し、そこに広視野X線モニターを搭載する予定である。

Establish of Gravitational Wave Astronomy with Gamma-Ray Burst and X-ray Transient Monitor

Daisuke YONETOKU[1,*,†], Yudai WAKASHIMA[1], Hajime YONEMOCHI[1], Shunsuke TAKATA[1], Hiroki SETA[1], Kazuki YOSHIDA[1], Asuka TOYANAGO[1], and Hirokazu IKEDA[2]

[1] Kanazawa University, Kakuma, Kanazawa, Ishikawa 920-1192, Japan,
[2] ISAS/JAX, Yoshinodai, Chuo-ku, Sagamihara, Kanagawa 252-5210, Japan

SUMMARY
Neutron star binary merger is one of the most promising candidates to detect the gravitational wave with the gravitational wave observatories, KAGRA, Advanced LIGO, VIRGO in the middle of construction. Then the short gamma-ray bursts (SGRBs) may be produced and emit huge amount of X-rays and gamma-rays. If we realize the all sky monitoring observations with X-ray imaging detectors aboard the micro-nano satellites, we strongly contribute to establish the new frontier of gravitational astrophysics. Kanazawa University will start the educational program to learn the space science and technology, and also develop 50 kg class of micro satellites until 2018-19. We are planning to install the X-ray wide field monitor aboard the satellite.

KEY WORDS:　Gamma-Ray Bursts; Gravitational Wave; X-ray; Wide Field Monitor

---

[*] Corresponding author. Associate Professor.
[†] E-mail: yonetoku@astro.s.kanazawa-u.ac.jp.
Received ***, Revised ***, Accepted ***.

1. Introduction

Gravitational wave (GW) observatories are now constructing whole over the world, and they, KAGRA, A-LIGO, and VIRGO will start full-scale observations in 2017–2018. The existence of GW is expected in the theory of general relativity, but its direct detection is very important issue for the verification of the general relativity and fundamental physics. The modern astronomy is mainly developed by the electro-magnetic wave observations, for example, radio, infrared, optical, X-ray and gamma-ray. The GW carries brand new information about strong gravitational fields and its time variation. Therefore we can say, today is the dawn of the GW astronomy. However, in the GW observations, the ability of the position localization for GW source is quite poor of about several degrees. This is not enough to discuss astrophysics because there are large amount of astronomical objects within their error circle, and we cannot determine the source and also cannot even measure the distance toward it. Therefore the electro-magnetic wave observations coinciding with the GW detection strongly support the physical argument of new frontier of GW astronomy. Especially the number of steady objects in X-ray and gamma-ray bands is quite smaller than the one of optical and infrared, so we can easily find new X-ray and gamma-ray transient sources.

The GW is emitted from the objects with the temporal variation of the strong gravitational field like supernova explosions and merging binaries of compact objects (neutron stars and/or black holes). Therefore a monitor of transient events with the wide field of view is thought to be one of the best methods to find the GW objects, and strongly solicited by the GW observers. In this paper, we propose the X-ray monitoring for the short gamma-ray bursts with 50 kg class micro-nano satellite which may contribute the establishment of the new field of GW astronomy.

This paper is organized as following. In section 2, we show the observational property of short gamma-ray bursts (SGRBs) and their event rate in the nearby galaxies. Especially we show that the extended soft X-ray emission following the short prompt emission will be a key to localize the SGRB position. In section 3, we introduce the possible solution of wide field X-ray imaging detector which can be aboard the micro-nano satellite. We also introduce developing X-ray imaging system with 1-dimensional silicon strip detector and coded aperture mask.

2. Short Gamma-Ray Bursts (SGRBs)

The gamma-ray bursts are recognized as the biggest explosions in the universe. We know two kinds of bursts, the long gamma-ray bursts (explosions of massive stars) and the short gamma-ray bursts (perhaps merging events of neutron star binaries). Here, the merging events of neutron star binaries, which may produce the short gamma-ray bursts (SGRBs), are the most promising candidate to detect the GW. In Figure 1, we show a typical lightcurve of SGRB. The first gamma-ray spike with the short time duration of ~1 second is the main emission, and the extended soft X-ray emissions lasting ~100 seconds are also following. The main emission of SGRB is thought to be generated in the narrowly collimated jet with an opening half angle of ~5 degrees, so we can detect the small fraction (~1/200) of all SGRBs. On the other hand, since the extended emission may be rather spread (roughly isotropic), we expect to observe the extended emission without prompt short spike. According to the sensitivity of GW observatories, only the nearby SGRBs within 300 Mpc (redshift of $z<0.08$) are detectable. The event rate of nearby SGRB may be small as shown in following description, then the Therefore it is better to focus the extended soft X-ray emission to detect SGRBs while we may miss the main short spike.

In Figure 2, we show the redshift distribution of bright SGRBs detected by BATSE aboard Compton Gamma-Ray Observatory during its 9 years operation. The red filled-squares are SGRBs with redshift measurements by optical spectroscopy, and black filled-circles are ones with redshifts estimated from characteristics of SGRBs (luminosity indicator; the Epeak – luminosity correlation by [1], which is similar to the well-known Epeak – luminosity correlation in long GRBs by [2] and [3]). As shown in the figure, we can say majority of SGRBs occur around the redshift of $z\sim1$, and nearby events within $z<0.1$ are quite rare. Using this dataset, we estimate the SGRB formation rate as a function of redshift with the non-parametric statistical method developed by several authors (e.g. [4] and [5]). The detail mathematical description is found in their papers.

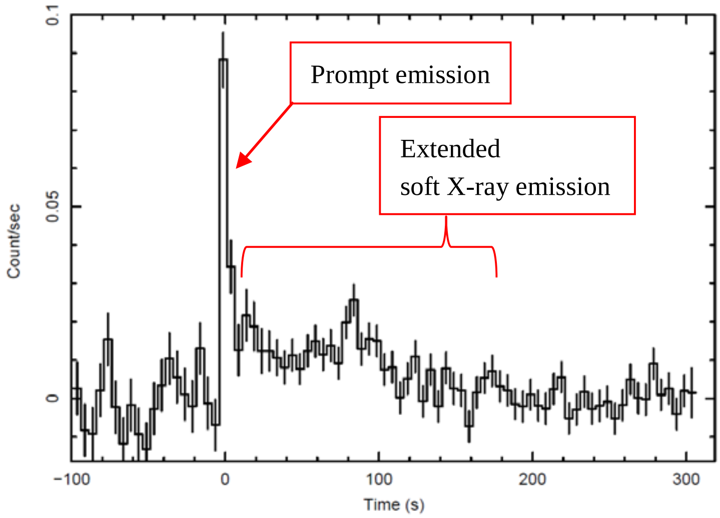

Figure 1. Example of lightcurve of SGRBs (SGRB 050724) detected by Swift/BAT. The first intense peak is the prompt emission of SGRB, and the extended soft X-ray emission lasting longer than 100 sec is following after the prompt emission.

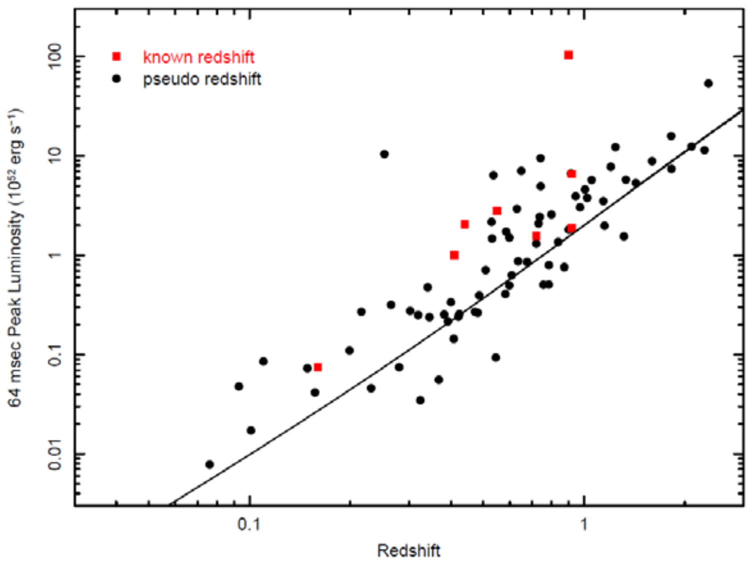

Figure 2. The redshift distribution of SGRBs estimated by the SGRB luminosity indicator (Epeak – Luminosity correlation). The red points are known redshift samples and the black points are the pseudo redshift samples observed by CGRO/BATSE detectors. The solid line is the flux limit of 4x10^{-6} erg/cm2/s.

In Figure 3, we show the SGRB event rate estimated by the redshift distribution of Figure 2 [6]. The local event rate at present universe is about 2x10^{-10} events/Mpc^3/yr. If we consider the jet collimation whose opening half angle of ~5 degrees, the total event rate may be roughly ~1 events/year in the whole sky. However this value is the lower limit because the dataset in Figure 2 are bright SGRBs and there are many dimmer SGRBs under the flux limit of Figure 2. Therefore we think the expected event rate is ~10 events/year in the whole sky. Anyway, the event rate is not so high, so it is essentially important to monitor the wide field (almost entire sky) to detect the extended soft X-ray emissions of SGRBs and localize their position. One of possible approach is to cover the almost whole sky with a group of micro-nano satellites.

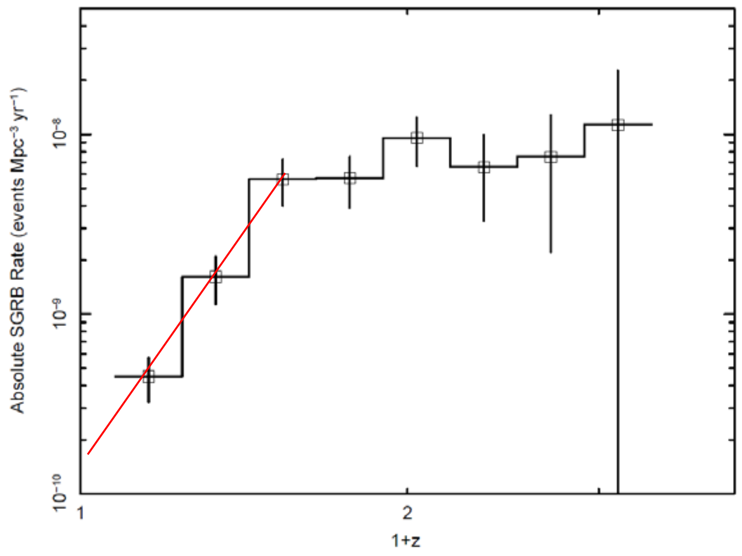

Figure3. The SGRB formation rate estimated by the redshift distribution of Figure 2.

3. X-ray imaging system for SGRBs

SGRBs accompanying GW detection must be close events within the redshift of z<0.08 (300 Mpc), so we expect that the apparent brightness of extended soft X-ray emission may be enough to detect with small X-ray detectors. According to nominal brightness of short GRBs, an expected X-ray fluence may be S>10^{-6} erg/cm^2, which is equivalent to the photon fluence of 300 photon/cm^2. Then we can localize their positions with small X-ray imaging detectors with ~100cm^2 effective area.

We are developing an X-ray imaging detector with a coded aperture mask as shown in Figure 4. The principle of X-ray imaging is to observe the shade of random coded pattern. When we calculate the 2-dimensional cross correlation function between the X-ray intensity map on the detector and the known mask pattern, the correlation degrees are proportional to the X-ray intensity of the astronomical sources. In mathematical point of view, the random mask has every wave-number vector space in Fourier transformation, so we can determine the source position in the real space to calculate the inverse Fourier transformation.

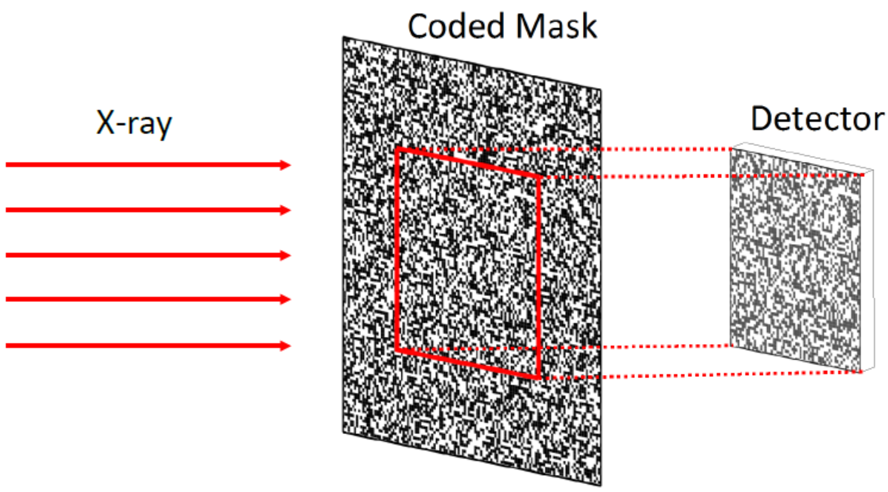

Figure 4. A schematic view of X-ray imaging detector with coded aperture mask.

We summarize the detector configuration which enables to be aboard the micro-nano satellite. Assuming the limited resources of the micro-nano satellite, we consider the 1-dimensional silicon and/or cadmium telluride imager. The effective area of detector module is about 19.2mm x 32mm (~6cm^2), and which has 64ch strip-type electrode with each width of 0.3mm (0.3mm x 64 = 19.2mm) as shown in Figure 5 (left). Their signal charges are readout by 64ch ASICs which is developed by ISAS/JAXA and Kanazawa University. The arrays of 16 detector modules (effective area of ~100cm^2) are used as 1-dimensional imager together with the coded aperture mask. Therefore we plan to use 32 detector modules for 2-dimensional imaging totally. The coded aperture mask made of tungsten is also designed with 0.3mm random slit, and set at 150mm in front of detector arrays. The localization accuracy is described as “$\theta = \tan^{-1}(2d/D) \sim 14$ arcmin”, here “d = 0.3mm” is the pitch of detector and mask, and “D = 150mm” is the separation length between them. If we change the “d” and “D”, we can also change the accuracy of the position determination of X-ray transient sources. We summarized the configuration of X-ray imaging system in Table 1.

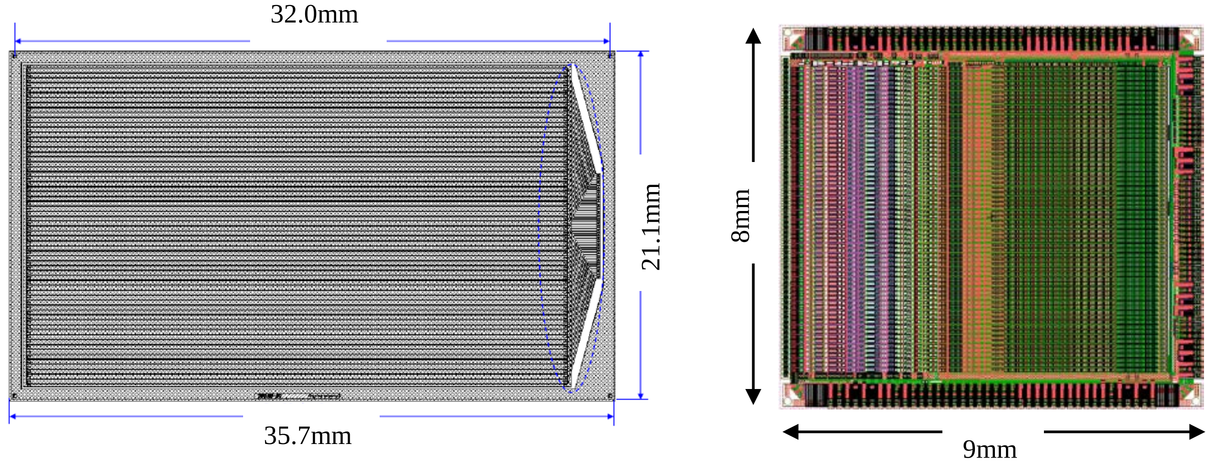

Figure 5. (Left) 64 channel silicon strip detector with 0.3mm pitch electrode. The fan-out structure is prepared for the purpose of direct connection between readout ASIC. (Right) physical layout of 64 channel readout ASIC developed by ISAS/JAXA and Kanazawa University.

Table 1. Configuration of X-ray imaging system

Configuration	Si or CdTe detectors (1 dimensional imaging detector for x- and y-axis each) with random coded aperture mask
Effective Area	200 cm^2 @ a few keV (100 cm^2 for each x- and y-dimension)
Size	150 mm x 300 mm x 150 mm (height) x 2 (x and y) including the coded mask
Mass	Less than 10 kg (5kg x 2)
Power	~ 20 W in total
Field of View	~1 steradian per detector (12 modules are required to monitor the whole sky)
Position accuracy	7 – 14 arcmin (geometrical: 14 arcmin, weight of photon statistics: ~7 arcmin)
Attitude accuracy	A few arcmin
Maneuver speed	Not necessary

We performed numerical simulations for the newly designed ASIC with T-SPICE simulator. In Figure 6, we show the noise level as a function of input capacitance of silicon strip detector. The red, green and blue plots show the effective threshold of readout for various current level for the charge sensitive amplifier. Here, we defined the threshold level as 4 sigma higher than the typical noise fluctuation. According to the current design of silicon strip detector, we estimate the capacitance of ~10pF for each strip. Therefore, in the case of 100uA (red), we may realize the readout from ~1keV X-ray signal for the detector capacitance of < 10 pF. Then the electric power for one ASIC will be ~100mW, and the net electric power will be 3.2W only for ASICs. Including FPGA, CPU and high voltage modules, we will integrate the entire system with the total electric power less than 20W.

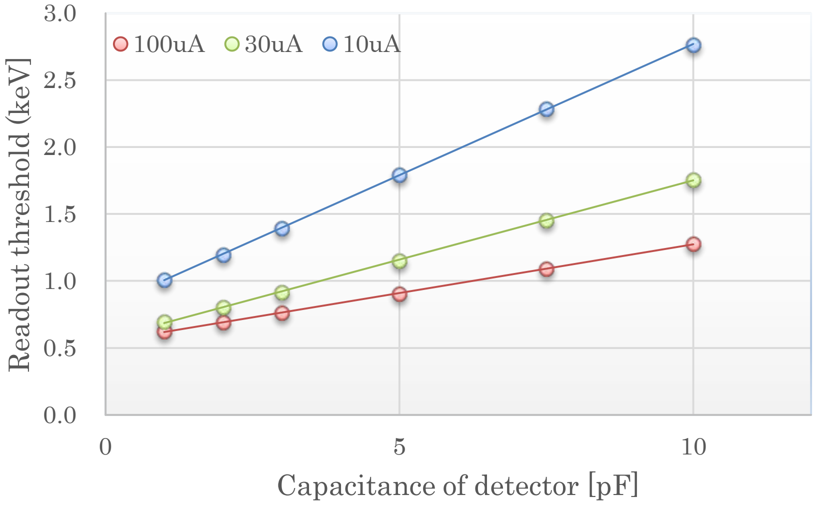

Figure 6. Estimated performance (the readout threshold as a function of input capacitance of detector) of readout ASIC with T-SPICE simulator. The red, green, and blue colors mean the different electric current (100, 30, 10 uA) in charge sensitive amplifier.

We demonstrate the X-ray imaging experiment using the cadmium telluride detector with handmade coded aperture mask with Pb string as shown in Figure 7 (left). We rotated the setup with 90 degrees, and observed the X-ray source of ^{57}Co (122keV) twice. The reconstructed and combined X-ray image is also shown in Figure 7 (right). The cross point is the X-ray position, and we can localize the position of astronomical X-ray objects.

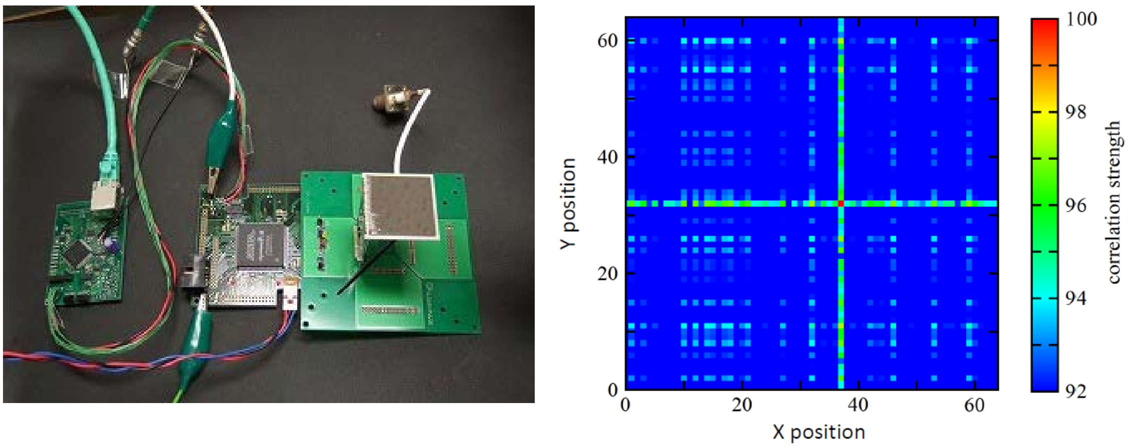

Figure 7. (Left) demonstration of 1-dimensional X-ray imaging system. (Right) X-ray image obtained with the setup shown in left panel. The cross point is the position of radio isotope.

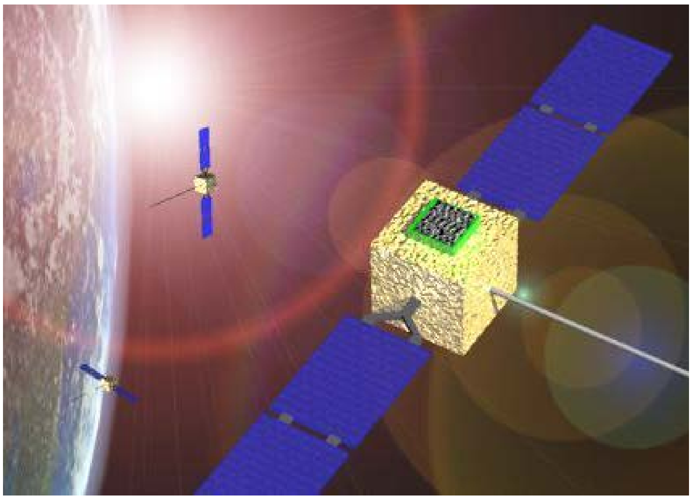

Figure 8. X-ray monitoring for the Whole sky with groups of micro-nano satellites.

4. Conclusion

The X-ray imaging detector described above has the wide field of view of ~1 steradian, but it is not enough to monitor the whole sky (4π) only by one satellite. Therefore, it is better to observe the whole sky with a group of micro-nano satellites distributing several orbits with different pointing attitude as shown in Figure 8. In the history of X-ray astronomy, such all sky imaging monitors have not been realized yet. This is a possible discovery space for the high energy astrophysics. These groups of micro-nano satellites can monitor many kinds of X-ray transients. So we may enable to perform the brand new X-ray observations, and strongly support not only GW observation but also the electro-magnetic wave observations. We think the whole sky monitor is one of the best ways to use a micro-nano satellite, and we hope to realize such a new field of science in cooperation of whole over the world.

(1) The gravitational wave (GW) observation is a new frontier of astronomy. The neutron star – neutron star merger in the nearby galaxies ($z<0.08$) is a most promising candidate to detect the GW.

(2) However, the GW observation has a poor capability to determine the position of the source. Therefore, the GW community strongly hopes the electromagnetic wave observatories to perform the synchronized observation with the GW detection.

(3) Especially, the neutron star mergers may produce short gamma-ray bursts. Therefore the wide field monitoring in X-ray and gamma-ray band effectively contributes the GW astronomy. However, the event rate of neutron star merger is not so high (about 10 events/year).

(4) Then the groups of nano-satellite with X-ray imaging system will realize the all sky monitoring, and also will open the new frontier of GW astronomy.

(5) We, Kanazawa University, will start an educational program to learn the space science and technology, and also develop 50 kg class of micro satellites until 2018-19. We will install the X-ray imaging system aboard the satellite. The GW facility will start the full-scale observation from 2018, so we strongly hope to support the GW observation with wide field X-ray instruments.

5. Acknowledgments

This work is supported by the Grant-in-Aid for Science Research (A) No. 25247038 (DY) and Grant-in-Aid for Scientific Research on Innovative Areas No. 25103507 (DY).

6. References

[1] Tsutsui, Ryo; Yonetoku, Daisuke; Nakamura, Takashi; Takahashi, Keitaro; Morihara, Yoshiyuki Monthly Notices of the Royal Astronomical Society, Volume 431, Issue 2, p.1398-1404, 2013

[2] Yonetoku, D.; Murakami, T.; Nakamura, T.; Yamazaki, R.; Inoue, A. K.; Ioka, K. The Astrophysical Journal, Volume 609, Issue 2, pp. 935-951. (2004)

[3] Yonetoku, D.; Murakami, T.; Tsutsui, R.; Nakamura, T.; Morihara, Y.; Takahashi, K. Publications of the Astronomical Society of Japan, Vol.62, No.6, pp.1495—1507

[4] Lynden-Bell, D., MNRAS, 155, 95 (1971)

[5] Efron, B. & Petrosian, V., ApJ, 399, 345 (1992)

[6] Nakamura, T.; Yonetoku, D.; Toyanago, A.; Takahashi, K., submitted to ApJL

