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

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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, Advanced 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 a new frontier of gravitational astrophysics. Kanazawa University will start an educational program to learn the space science and technology, and also develop 50 kg class of micro satellites, named Kanazawa-SAT[3] (cube-sat) until 2018-19. We are planning to install the X-ray wide field monitor aboard the satellite.

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

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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 Kanazawa-SAT[3] (金沢キューブサット) 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。

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

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1. Introduction

Gravitational wave (GW) observatories are now constructing whole over the world, and they, KAGRA, A-LIGO, and A-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 verification of the general relativity and fundamental physics. 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, a capability of 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, electro-magnetic wave observations coinciding with the GW detection will 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 coalescence binaries of compact objects (neutron stars and/or black holes). Therefore the monitor of transient events with wide field of view is thought to be one of the best methods to find GW objects, and strongly solicited by 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 introduce the observational property of short gamma-ray bursts (SGRBs) and their event rate in the nearby galaxies referring the paper by [1]. Especially we show that an extended soft X-ray emission following the short prompt emission will be a key to localize the SGRB position. In section 3, we introduce a 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. We show a sensitivity of the X-ray detector compared with the Swift-BAT instrument in section 4. Finally, in section 5, we notice an importance of ground based antenna systems to realize the observation with group of micro-nano satellites.

2. Short Gamma-Ray Bursts (SGRBs)

Gamma-ray bursts are recognized as the biggest explosions in the universe. We know two kinds of bursts, long gamma-ray bursts (explosions of massive stars) and 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 [2] [3], 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. An event rate of nearby SGRB may be small as shown in the following description. 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 [1]. 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 E_{peak}–luminosity correlation by [4], which is similar to the well-known E_{peak}–luminosity correlation in long GRBs by [5] and [6]). 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. [7] and [8]). The detail mathematical description is found in their papers.

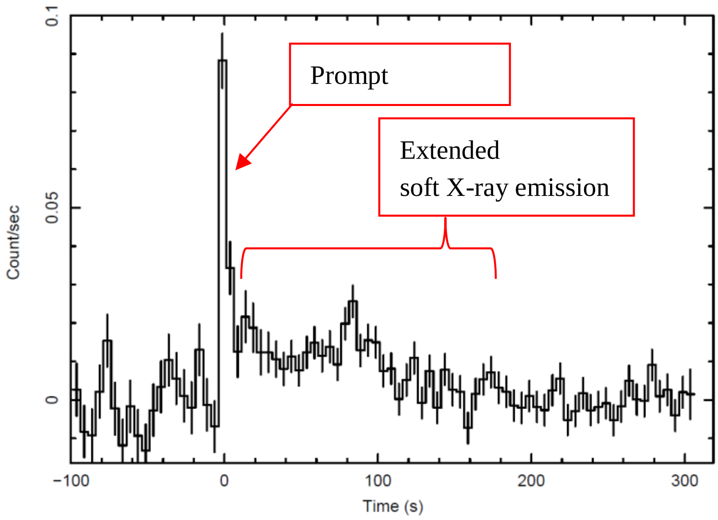

Figure 1. Example of lightcurve of SGRBs (SGRB 050724) detected by Swift/BAT. The first intense peak is the prompt emission of SGRB, and the extended soft X-ray emission lasting longer than 100 sec is following after the prompt emission.

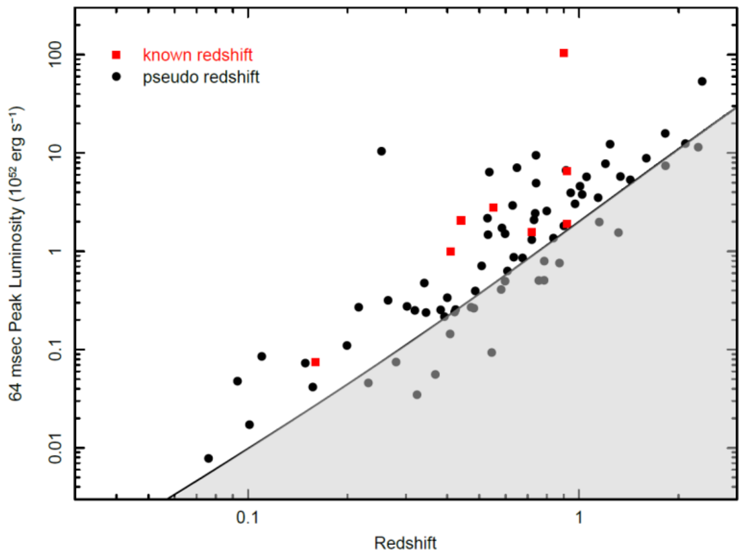

Figure 2. The redshift distribution of SGRBs estimated by the SGRB luminosity indicator (E_{peak}–Luminosity correlation). Red points are known redshift samples and black points are the pseudo redshift samples observed by the CGRO/BATSE. The solid line is the flux limit of $4x10^{-6}$ erg/cm^2/s [1].

In Figure 3, we show the SGRB event rate estimated by the redshift distribution of Figure 2 [1]. 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 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 positions. One of possible approach is to cover the almost whole sky with a group of micro-nano satellites.

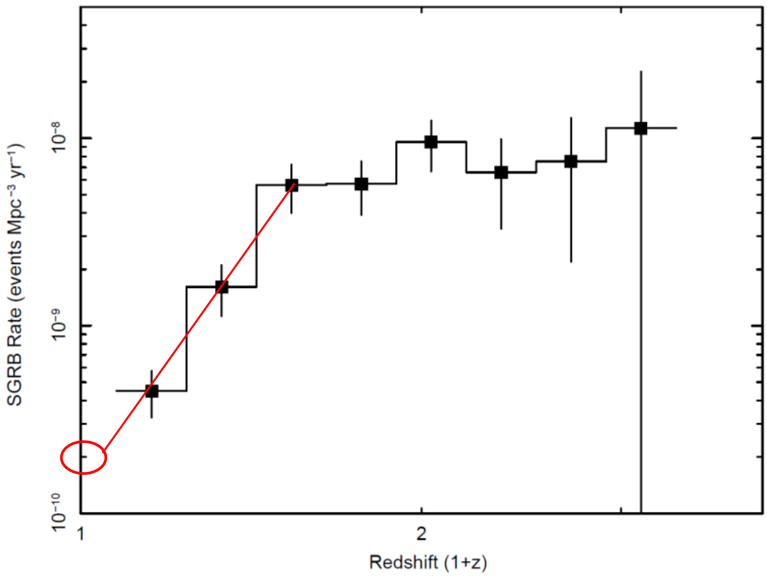

Figure3. The SGRB formation rate estimated by the redshift distribution of Figure 2.

3. X-ray imaging system for SGRBs

SGRBs accompanying the 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 brighter than 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 ~100 cm^2 detector 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 reconstruct the source position without any mimic signals in the real space to calculate the inverse Fourier transformation.

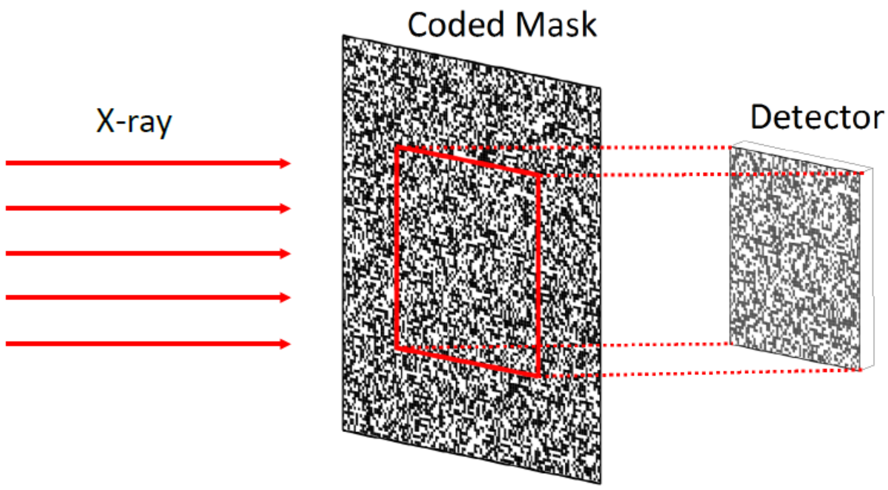

Figure 4. A schematic view of X-ray imaging detector with coded aperture mask.

We summarize the detector configurations which enable to be aboard the micro-nano satellite. Assuming the limited resources of the micro-nano satellite, we consider the 1-dimensional silicon imaging detector. The effective area of detector module is about 19.2 mm x 32 mm (~6 cm^2), and which has 64ch strip-type electrode with pitch width of 0.3mm (0.3 mm x 64 = 19.2 mm) 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 8 detector modules (detector area of ~50 cm^2) are used as 1-dimensional imager together with the half-coded aperture mask. Therefore we plan to use 16 detector modules for 2-dimensional imaging totally. The coded aperture mask made of gold plated nickel or tungsten with 0.3mm random slit is also designed, and set at the height of 150 mm in front of detector arrays. The localization accuracy is described as "$\theta = \tan^{-1}(2d/D) \sim 14$ arcmin", here "d = 0.3 mm" is the pitch of detector and mask, and "D = 150 mm" 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.

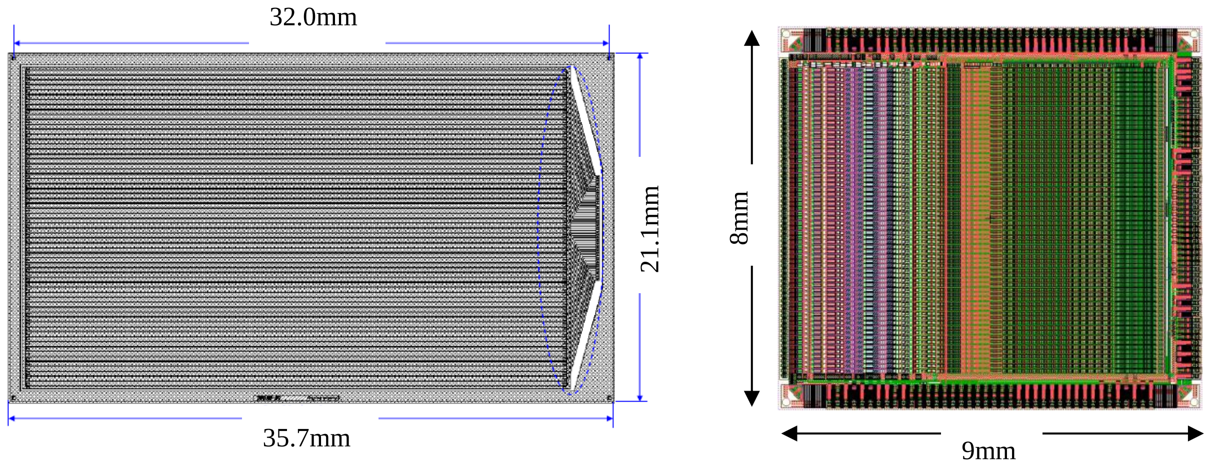

Figure 5. (Left) 64 channel silicon strip detector with 0.3mm pitch electrode. The fan-out structure is prepared for the purpose of direct connection between readout ASIC. (Right) physical layout of 64 channel readout ASIC developed by ISAS/JAXA and Kanazawa University.

Table 1. Configuration of X-ray imaging system and Satellite

Detector	
Configuration	1 dimensional Si imaging detector for x- and y-axis each with random coded aperture mask
Energy Range	1 – 20 keV
Detector Area	100 cm^2 @ a few keV (50 cm^2 for each x- and y-dimension)
Size	70 mm x 300 mm x 150 mm (height) x 2 (x and y) including the coded mask
Mass	Less than 8 kg (< 4kg x 2)
Power	~ 20 W in total
Field of View	~1 steradian (12 satellites are required to monitor the whole sky)
Position accuracy	7 – 14 arcmin (geometrical: 14 arcmin, weight of photon statistics: ~7 arcmin)

Satellite	
Size	50 cm x 50 cm x 50 cm
Mass	Less than 50 kg
Attitude accuracy	A few arcmin (which is less than the position accuracy of X-ray detectors)
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 ~10 pF for each strip. Therefore, in the case of 100 μA (red), we may realize the readout from ~1 keV X-ray signal for the detector capacitance of < 10 pF. Then the electric power for one ASIC will be ~100 mW, and the net electric power will be 1.6 W only for ASICs. Including FPGA, CPU and high voltage modules, we will integrate the entire system with the total electric power less than 20W.

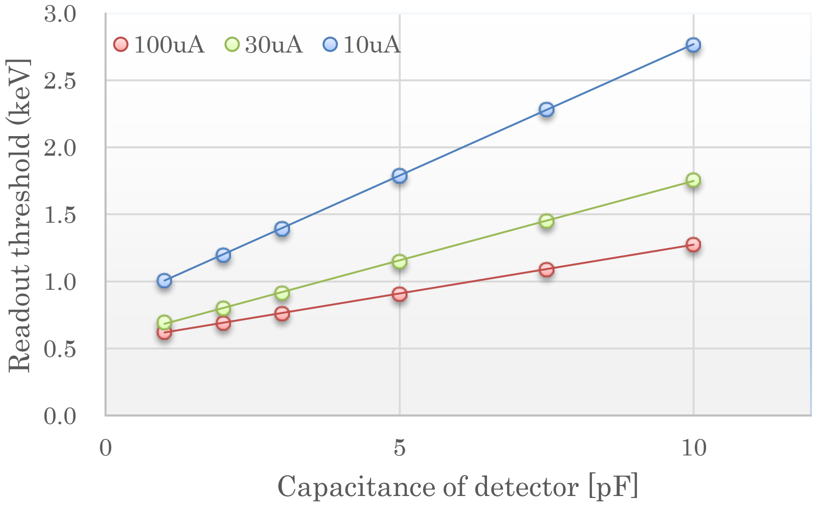

Figure 6. Estimated performance (the readout threshold as a function of input capacitance of detector) of readout ASIC with T-SPICE simulator. The red, green, and blue colors mean the different electric current (100, 30, 10 uA) in charge sensitive amplifier.

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.

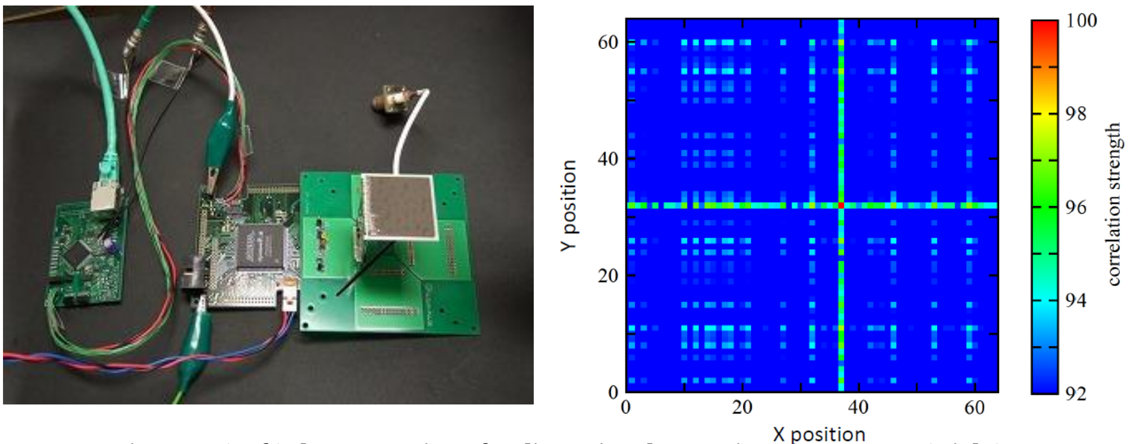

Figure 7. (Left) demonstration of 1-dimensional X-ray imaging system. (Right) X-ray image obtained with the setup shown in left panel. The cross point is the position of radio isotope.

4. Sensitivity of X-ray imaging detector

We calculated the sensitivity of X-ray imaging detector. In this calculation, we consider the cosmic X-ray background (CXB) and the galactic ridge X-ray emission. We should include the contamination of X-ray sources and non-X-ray background from surrounding materials, but we did not include them here. We used the functional form of CXB by [9] and one of the galactic ridge X-ray emission by [10], and we estimated the net X-ray count rates between 1 and 20 keV are 13.5 photons/cm^2/s/str and 55.6 photons/cm^2/s, respectively. The gamma-ray spectrum of GRBs are well described by a smoothly broken power-law [11]. The typical photon index of low- and high-energy parts are -1 and -2.5, respectively.

In figure 8, we show the trigger sensitivities for the photon flux with 8σ significance as a function of peak energy (typical energy which corresponds to the energy at the maximum flux of νF_ν spectrum). Then we assumed the detector configuration listed in Table 1. We show two cases of background conditions, CXB only (high galactic latitude – red solid line) and CXB with Galactic Ridge emission (low galactic latitude – blue solid line). For easy comparison, we also show the trigger sensitivity of Swift-BAT instruments (effective energy range of 15 – 150 keV and detecting area of 5200 cm^2). As shown in figure 8, small X-ray imaging detector with the area of 100 cm^2 has better sensitivity for the extended soft X-ray emission from SGRBs and softer GRBs (X-ray flash and X-ray rich GRBs) with the peak energy lower than 10 keV even if the galactic ridge emission is in the field of view.

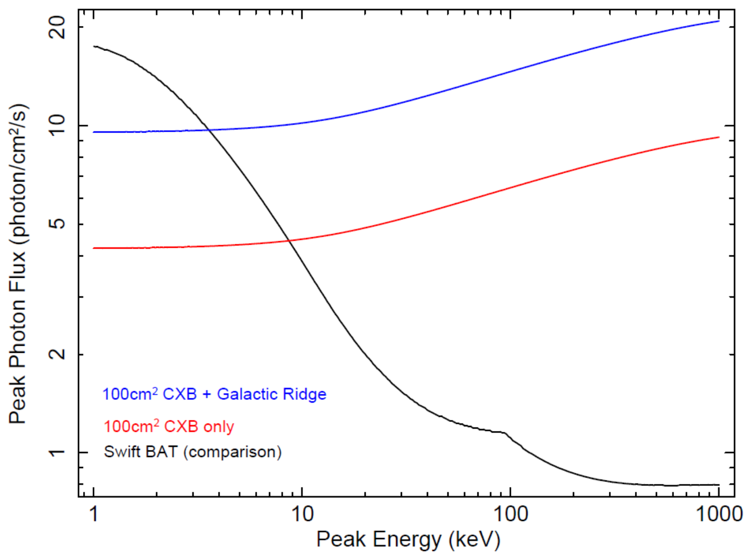

Figure 8. Sensitivity of X-ray imaging detector. Red and Blue solid lines show different background cases of CXB only and CXB with galactic ridge emission, respectively. The Blue solid line is the sensitivity of Swift-BAT.

5. Alert systems (ground based antennas)

As the first step of SGRB observation coincides with GW detection, even the timing measurement is expected from the GW community even if localization cannot be performed. We have no knowledge about the origin of GW sources, so the additional information from electro-magnetic observations is surely important. As the next step, of course, the rough localization will be important. Our imaging capability is rather poor to identify the individual galaxies. However if we find a candidate of group of galaxies including SGRB, we may discuss several physical quantities of GW sources, for example total energy of GW and electro-magnetic radiation (typical size of group of galaxies is 5 Mpc and the distance range of GW observation is 300 Mpc. This is 2% accuracy in distance scale).

If we will enable to prepare worldwide alert system, the follow-up observations by larger observatories in X-ray, optical, near infrared and radio are effectively worked. Some kinds of methods are considered as following.

(1) Relay satellites

The Swift satellite uses the TDRSS relay satellite to send a real time alert of GRB localization within several seconds. In Japan, DRTS *Kodama* satellite is also used for the real time data transfer from the International Space Station, *Daichi* satellite and so on. However, in general, the transponder to connect these relay satellites are quite expensive in view of total cost of micro-nano satellite system. But this is one of a possibility to realize the real time alert system.

(2) Ground antennas

The past *HETE-2* satellite realized the first real time alert system with 13 ground antennas constructed around the equator. If we choose the equatorial orbit, we will use similar system for the real time alert. The future *SVOM* GRB satellite will extend a large amount of ground based stations between 30 degrees of north and south latitude. This global system will help the real time contact of micro-nano satellites.

(3) Contribution from amateur

Amateur radio operators may be able to contribute the operation of micro-nano satellite. They have already helped the operation of several small satellite project. If they will agree with the scientific motivations with group of satellites, their network will strongly help the real time contact.

Anyway, the global ground stations are key to operate the group of micro-nano satellites, and it is difficult to realize them by a small team. We hope to cooperate with several projects with similar plans to use group of satellites.

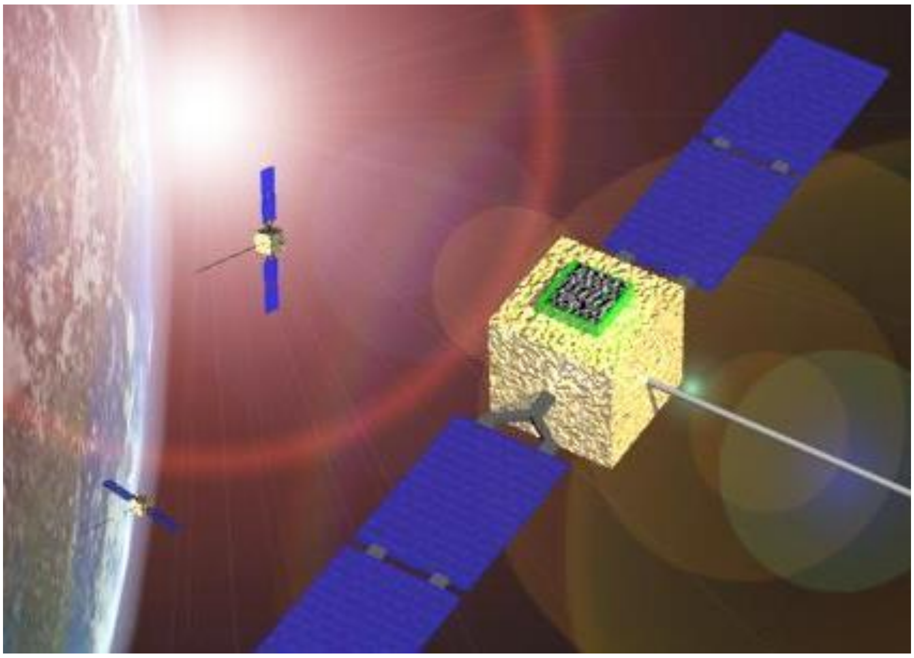

Figure 9. X-ray monitoring for the Whole sky with groups of micro-nano satellites.

6. 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 the group of micro-nano satellites distributing several orbits with different pointing attitude as shown in Figure 9. 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 group of micro-dnano satellites 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, named Kanazawa-SAT[3] (cube-sat) 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.

7. Acknowledgments

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