Searching for Ultraviolet Transients with a Small Telescope
Final Technical Report for SURF

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ABSTRACT

In this project, I focus on exploring the possibility of a UV telescope based on a mini satellite with mass less than 100kg and size no larger than a suitcase. Main goal for the UV telescope would be detecting the supernova shock-breakouts (SB). First, calculations that can give reasonable estimations of SBs that can be detected was chosen and tested (using Mathematica). With this, I adjusted the detector's parameters (pixel scale, effective area) while comparing the signal to noise ratio (S/N), limit distance, field of view and etc., and then got to the conclusion that it's quite hopeful to realize the search for UV transients with a small telescope. The maximum count rate is a critical parameter in the choice of the detector. To the end, I am exploring GALEX (an all-sky UV mission) data to estimate the different background count rate. Based on GALEX UV sky data, I studied the brightness distribution of the UV sky and then all sky is mapped to get the evaluation of diffuse background.

1. Introduction

Supernovae are relatively rare events within a galaxy and those in other galaxies cannot be predicted with accuracy. Early detection of supernova shock breakout is thus difficult, but which is indeed crucial because it can provide important information for most scientific interests in supernovae. The first clear-out discovery of shock break-out is in X rays(Soderberg et al. (2008)), but ultraviolet(UV) should also work well. A relevant prediction article is Klein & Chevalier (1978).

In most current astro space missions, large and massive instruments are involved which require large budget and long preparation time. Telescopes like these have high resolution power to see every details of the universe. However, if the goal is just detecting transients, then maybe much more *modest* space mission is well enough, or even better. These *nimble* projects, with shorter preparing time, can take full advantadge of the state-of-art technology with smaller budget and frequent launches.

With motivations like those above, *Less is More*[LIM] — a program considering astronomical satellites with mass budget of less than $100kg$, has started and now is still in dream-phase. This summer, my work is to see whether it's possible to detect UV transients based on a small satellite with size of a suitcase and mass less than $100kg$. One of the biggest restrictions is the size of the telescope. Although transient detection does not require high resolution power, we cannot say for sure that with such a small telescope , it's ever possible to distinguish a supernova shock break-out in a sea of galaxies. After rough evaluation of the detector's effective area that the telescope needs for detection, I prove that it's quite promising to build a mini telescope for UV transient detection. Then, a detailed study of the UV background of all sky is performed to get the precise UV diffuse background.

2. Main Approaches

Suppose a supernova shock break-out happens at a distance D, and a telescope looking in the right detection. The wanted signal is shock break-out and the telescope will also receive noise from the over-all UV background of the universe and the UV brightness of the host galaxy. If a good enough signal to noise ratio(S/N) and the limit distance of detection are already known, effective area for the detector can be calculated.

3. Reproduce light curve

In my calculation, a simple model from Rabinak & Waxman (2010) is adopted to get the light curve of a supernova shock break-out. Based on some simplified assumptions, it gives the phototspheric temperature and radius of the shock break-out for typical red super giants(RSG) and blue super giants(BSG) as followed

$$\text{RSG: } r_{ph}(t) = 3.3 \times 10^{14} f_\rho^{-0.0062} \frac{E_{51}^{0.41}\kappa_{0.34}^{0.093}}{(M/M_\odot)^{0.31}} t_5^{0.81} cm \tag{1}$$

$$\text{BSG: } r_{ph}(t) = 3.3 \times 10^{14} f_\rho^{-0.0036} \frac{E_{51}^{0.39}\kappa_{0.34}^{0.11}}{(M/M_\odot)^{0.28}} t_5^{0.78} cm \tag{2}$$

and

$$\text{RSG: } kT_{\rm ph}(t) = 1.6 f_\rho^{-0.037} \frac{E_{51}^{0}.027 R_{*,13}^{1/4}}{(\frac{M}{M_\odot})^{0.054}\kappa_{0.34}^{0.28}} t_5^{-0.47} eV \tag{3}$$

$$\text{BSG: } kT_{\rm ph}(t) = 1.6 f_\rho^{-0.022} \frac{E_{51}^{0.016} R_{*,13}^{1/4}}{(\frac{M}{M_\odot})^{0.033}\kappa_{0.34}^{0.27}} t_5^{-0.47} eV \tag{4}$$

Here $E = 10^{51}E_{51}erg$, $t = 10^5 t_5 s$, and $\kappa = 0.34\kappa_{0.34} cm^2/g$. R_* is the radius of the progenitor star. E is the ejected energy. M is its mass. f_ρ depends on the structure of the progenitor star, but as shown in Rabinak & Waxman (2010), the results are not very sensitive to the value of f_ρ. κ is a time and space independent opacity. k is the Boltzmann constant.

The ratio of the color temperature ($T_{\rm col}$) and effective photospheric temperature ($T_{\rm ph}$) can be calculated using the OP table opacities (and Equation (20) in Rabinak & Waxman (2010)).

Detailed calculation is performed in the original paper, and here for rough estimation I just use the conclusion that over the relevant time scale, $t \sim 1$ day,

$$T_{col}/T_{ph} \approx 1.2 \tag{5}$$

This relation does not hold for large and too small t. But for simplification, it's reasonable to regard this always correct for the needed time range $t_{\rm day} = 0 \sim 10$. Corrections will be made in the future if more accurate standards are necessary.

Assuming shock break-out is a black body emission, the model specific intensity, f_λ, is given by

$$f_\lambda(\lambda, t) = (\frac{r_{\rm ph}}{D})^2 \sigma T_{\rm ph}^4 \frac{kT_{\rm col}}{hc} g_{BB}(hc/\lambda k T_{\rm col}) e^{-\tau\lambda} \tag{6}$$

where

$$g_{\rm BB}(x) = \frac{15}{\pi^4} \frac{x^5}{e^x - 1} \tag{7}$$

D is the distance to the source, and $\tau_\lambda$is the extinction optical depth at λ. Pay attention that the units in Rabinak & Waxman (2010) are not completely correct, the equations I put here are already corrected.

Using these equations given above, I can calculate the brightness of a supernova. Comparison of my result and those from Rabinak & Waxman (2010)) are $Fig.1$&$Fig.2$

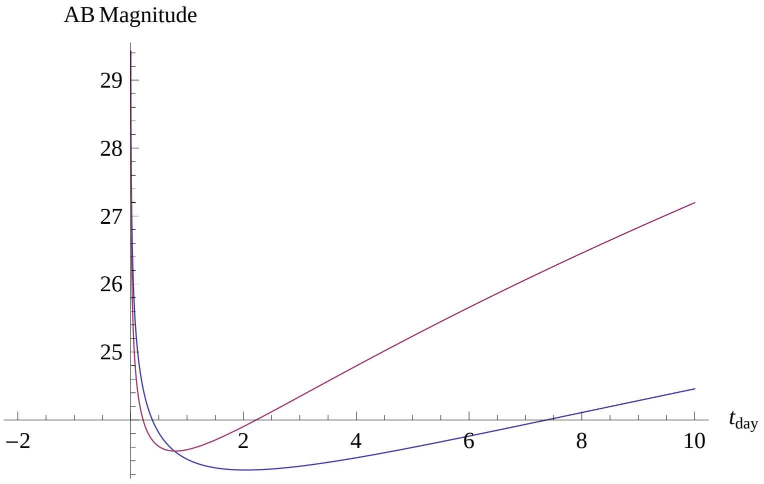


Fig. 1.— My reproduced graph. The blue line is for the NUV, the purple one is for the FUV. This calculation is based on the progenitor parameters and extinction given in Rabinak & Waxman (2010)

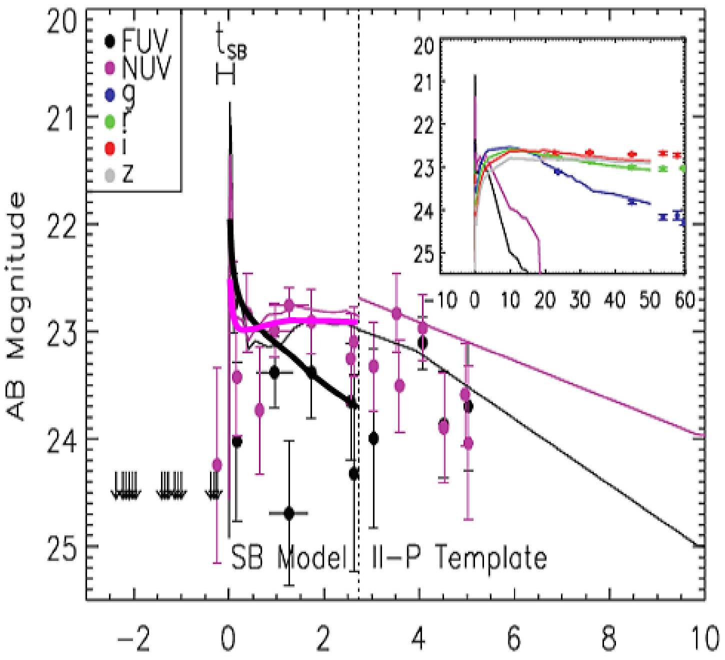


Fig. 2.— Original graph (Rabinak & Waxman (2010)). Thin lines are the numerical model calculations of Gezari et al. (2008), the over laid thick lines are the results of Rabinak & Waxman (2010) due to similar progenitor parameters and extinction.

4. Effective Area

Now, knowing how to produce the light curve of shock break-out, the relations between effective area, full width of half width(FWHM) and field of view (FOV) is studied in this section.

In the rest of this paper, $w = max[FWHM, pixelscals]$.

I present the calculation result of the needed effective area as a function of w based on (1) different limited distance; (2) different solid angle of FOV (while the rate of supernova per year is fixed) (3) different rate of supernova per year (while solid angle of FOV is fixed)

In this case, I take the parameters of *SN1987A* and *SNLS-04D2dc* for BSG and RSG calculation respectively. Details of these parameters are in §*Method*.

So when D is fixed, $A_{\rm eff}$ can be expressed as a function of $w(arcsec)$ (which is now taken as FWHM) and S/N ratio.

$$A = \frac{(S/N)^2}{\Delta t f^2 \frac{\Delta\lambda}{hc/\lambda}}[f + (10^{-m_{\rm gal}/2.5} + 10^{-m_{\rm bac}/2.5})(\pi w^2)] \tag{8}$$

S/N ratio represents how "good" the image is. For detecting transients, a S/N ratio of 5 is enough for us to distinguish the supernova. In the following calculation, $S/N = 5$.

Plot effective area as a function of w, with different D.(Fig. 1& Fig. 2)

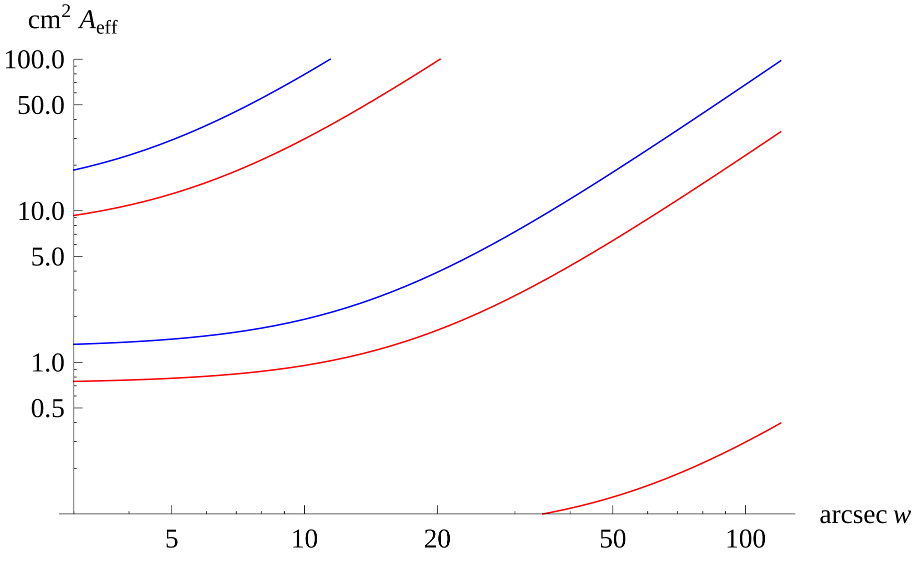


Fig. 3.— This is for FUV range. $D = 1Mpc \times 10^{1.5}, 10^2, 10^{2.5}$ respectively. The blue lines are the results for BSG and red lines are the results fo RSG. This graph is plotted within the range of $x \in [3, 120]$ and $y \in [0.1, 100]$. The BSG line for $D = 1 \times 10^{2.5}$ is out of range.

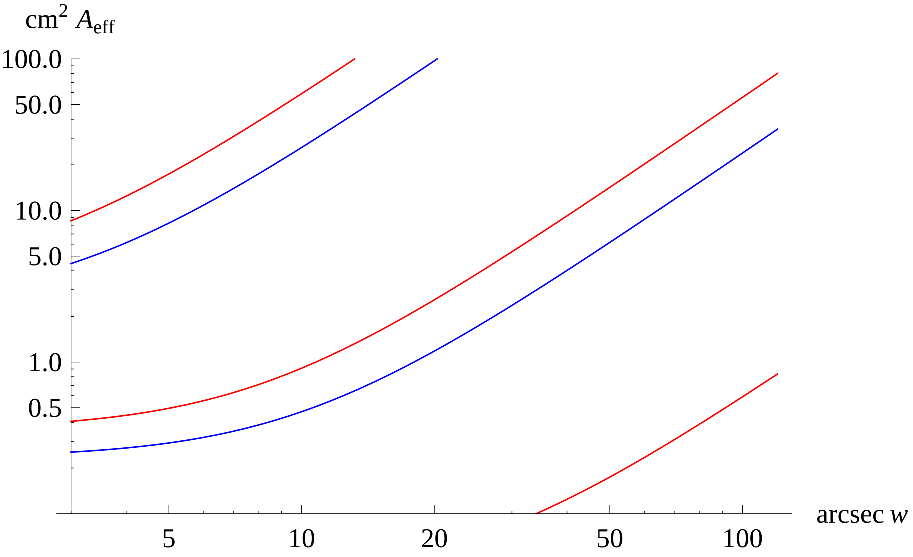


Fig. 4.— This is for NUV range. $D = 1Mpc \times 10^{1.5}, 10^2, 10^{2.5}$ respectively. The blue lines are the results for BSG and red lines are the results fo RSG. This graph is plotted within the range of $x \in [3, 120]$ and $y \in [0.1, 100]$.

The limit distance (D) can also be regarded as a function of solid angle of FOV (Ω) and rate of supernova breakout)$S_{\rm SN}$.

$$D = \sqrt[3]{\frac{3N}{6 \times 10^{-5}\Omega}} \times 3.086 \times 10^{24} cm \tag{9}$$

If here, I take $S_{\rm SN} = 10/year$, and 6×10^{-5} is the SB rate per year per Mpc^3.

Plot effective area as a function of w, with different Ω.

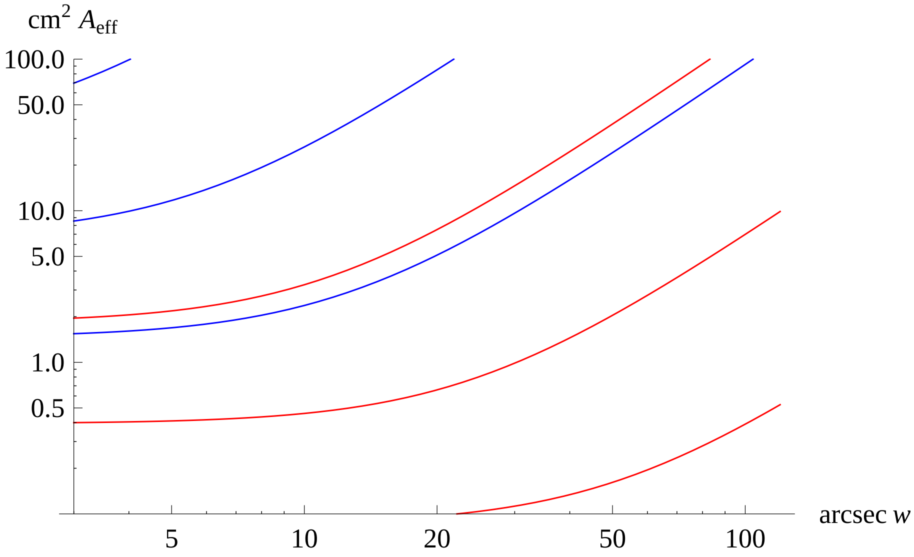


Fig. 5.— This is for FUV range. $\Omega = 4\pi, 4\pi \times 0.1, 4\pi \times 0.01$ respectively. The blue lines are for BSG and red lines for RSG.This graph is plotted within the range of $x \in [3, 120]$ and $y \in [0.1, 100]$.

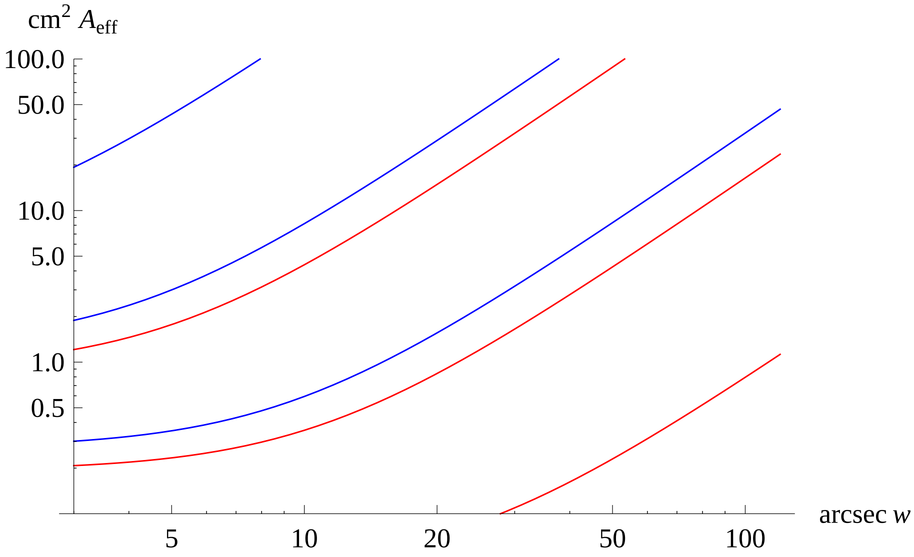


Fig. 6.— This is for NUV range. $\Omega = 4\pi, 4\pi \times 0.1, 4\pi \times 0.01$ respectively. The blue lines are for BSG and red lines for RSG.This graph is plotted within the range of $x \in [3, 120]$ and $y \in [0.1, 100]$.

Then, take $\Omega = 4\pi \times 0.05$. Plot effective area as a function of w, with different S_{SN}.

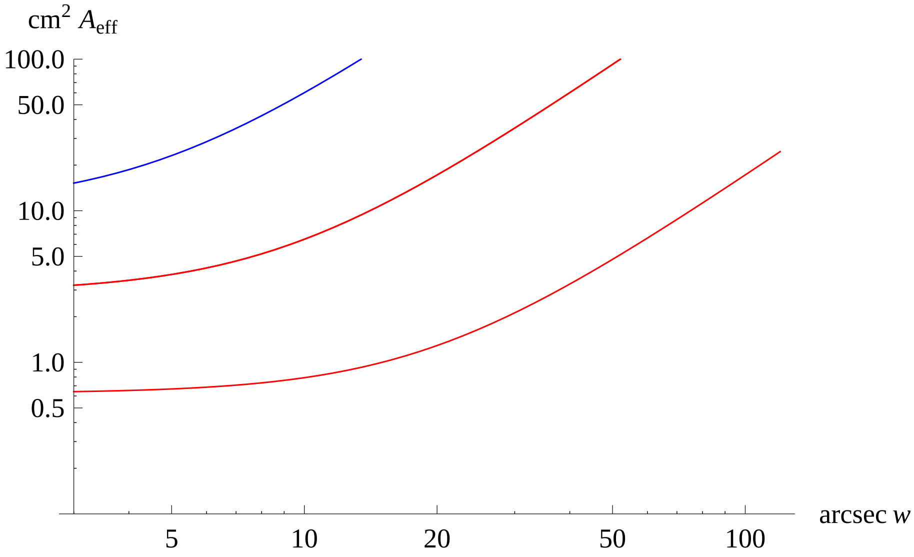


Fig. 7.— This is for FUV range.$S_{\text{SN}} = 10, 100, 1000$respectively. The blue lines are for BSG and red lines for RSG. This graph is plotted within the range of $x \in [3, 120]$ and $y \in [0.1, 100]$.

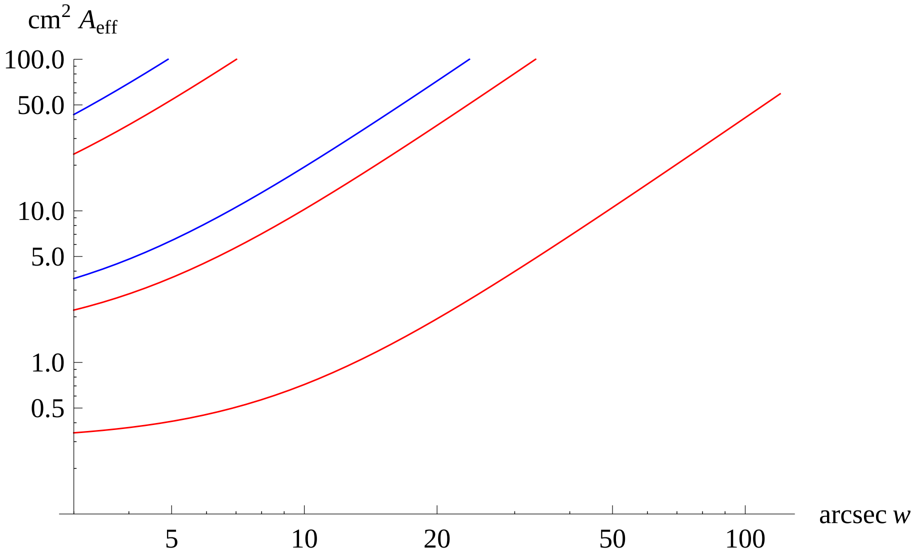


Fig. 8.— This is for NUV range.$S_{\text{SN}} = 10, 100, 1000$respectively. The blue lines are for BSG and red lines for RSG. This graph is plotted within the range of $x \in [3, 120]$ and $y \in [0.1, 100]$.

It can be seen from these 3 sets of graphs that for some relatively small w ($w < 15$, for example), the effective area of the detector need not to be too large. Often 20 cm^2 can already get good results for NUV band. FUV band always needs larger effective area, and maybe a small telescope is not appropriate for careful FUV observation. But because it's still unknown what is the best wavelength for UV transient detection, the overall results show that this proposal is very promising.

5. Diffuse UV background

The maxium count rate is crucial in deciding the detector's size. Only rough estimations cannot be regarded as reliable in our further study. A careful study of diffuse UV background is performed as below. I use data from GALEX(an all-sky UV survey telescope) archive.

First, images with most details are studied carefully to see the distribution of brightness within one field. Each tile is divided into 5 concentric circles and mean value of each circle is calculated and histogram of each circle is plotted in the same graph so as to compare the distribution of different parts of the same tile.

Data from *Deep Imaging Survey(DIS)*, with longest exposuer time, is used in this first step to unveil the brightness distribution within one tile. All of the 338 tiles in DIS newest release are processed in the way described in the last paragraph. Here below are some samples of my results $(Fig9 \sim 16)$.

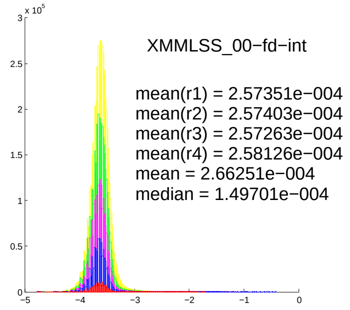


Fig. 9.— Histogram of FUV intensity map. X axis is log_{10} for the value.

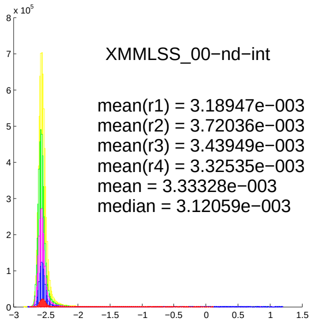


Fig. 10.— Histogram of NUV intensity map. X axis is log_{10} for the value.

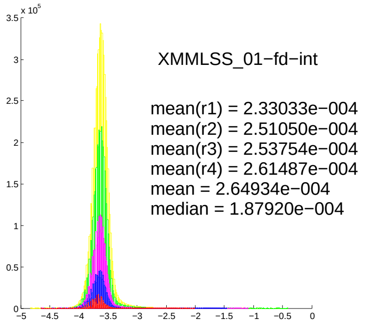


Fig. 11.— Histogram of FUV intensity map. X axis is log_{10} for the value.

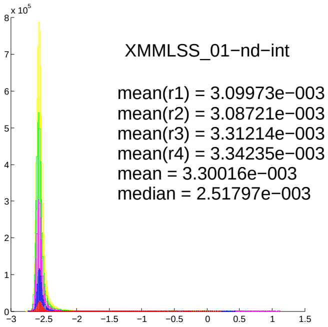
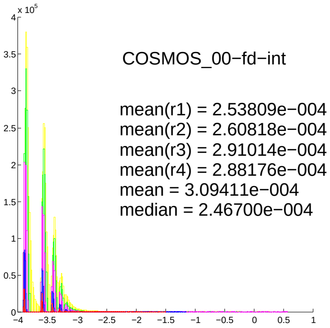


Fig. 12.— Histogram of NUV intensity map. X axis is log_{10} for the value.



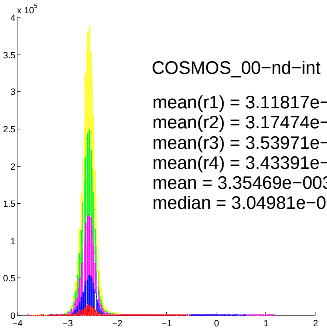
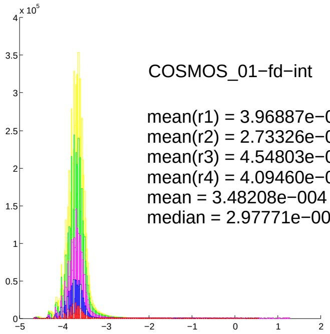


Fig. 13.— Histogram of FUV intensity map. X axis is $log(10)$ for the value

Fig. 14.— Histogram of NUV intensity map. X axis is $log(10)$ for the value



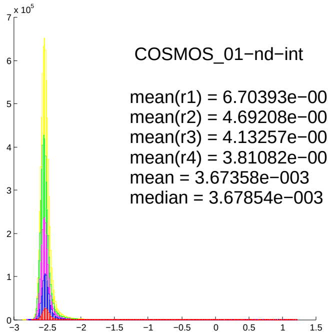


Fig. 15.— Histogram of FUV intensity map.X axis is $log(10)$ for the value

Fig. 16.— Histogram of NUV intensity map. X axis is $log(10)$ for the value

In these graphs, it's easy to see that histograms of each concentric circle almost always have the same distribution. This is actually a feature shared by most of the DIS tiles. Only exceptions are like those tiles looking directly at M31.

DIS only covers a small part of the sky. In order to get a complete estimation of all sky, data from *All Sky Survey(AIS)*(more than 28000 tiles) is adopted. Using the conclusions given in the last paragraph, we can simply replace most tiles with its mean value. The final result is Fig.17&Fig.18

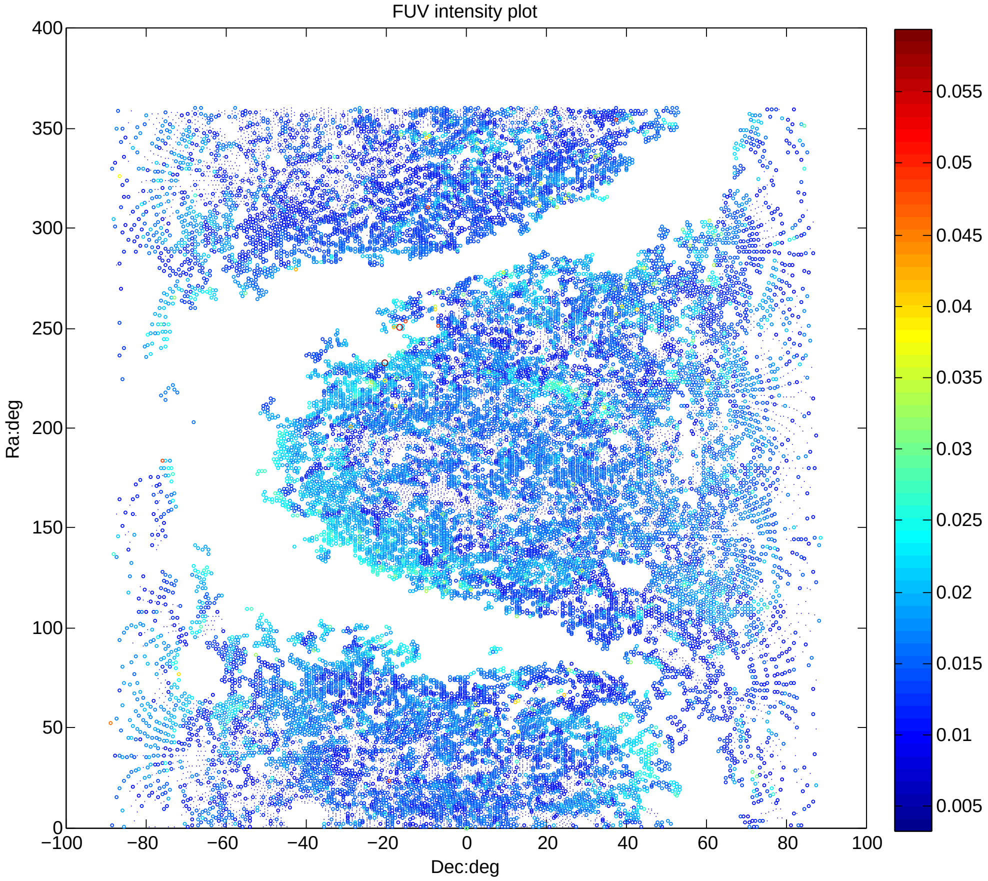


Fig. 17.— This is the all-sky FUV intensity plot. x,y axes correspond to declination and ascension. Each point in the graph is the center of one tile. Mean value of that tile can be read from the color bar(because the color changes discretely, so some minor difference is actually eliminated). The radius of each circle/point is also diffrent. Larger radius corresponds to higher mean value.

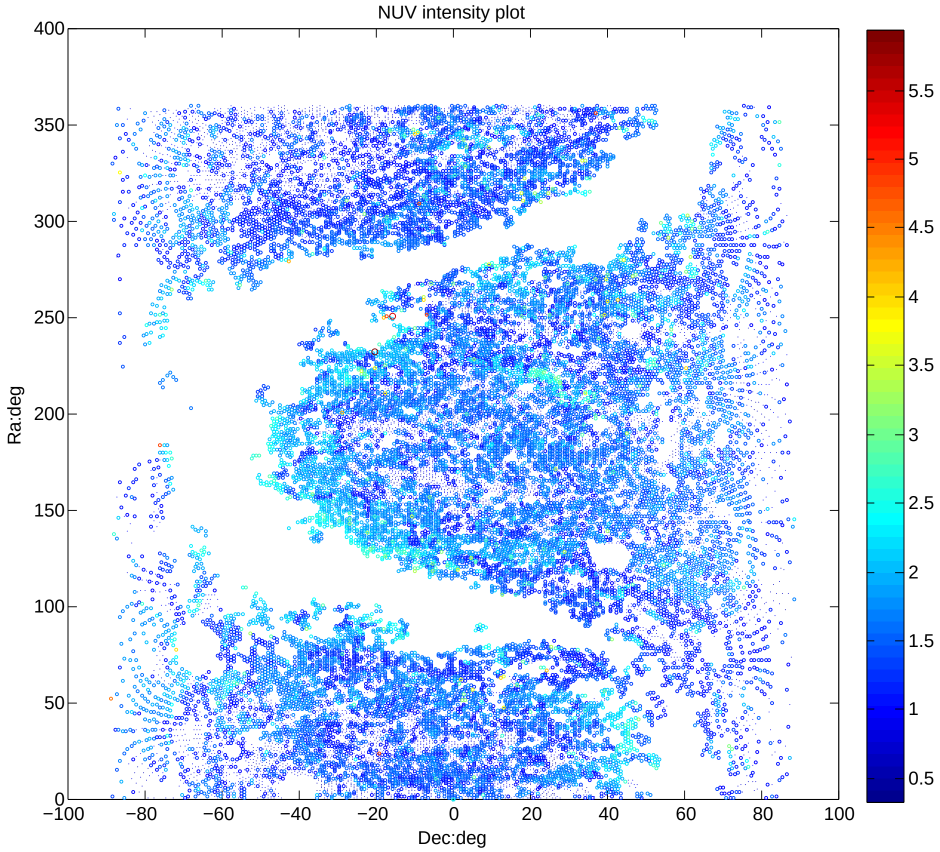


Fig. 18.— This is the all-sky NUV intensity plot. x,y axes correspond to declination and ascension. Each point in the graph is the center of one tile. Mean value of that tile can be read from the color bar(because the color changes discretely, so some minor difference is actually eliminated). The radius of each circle/point is also different. Larger radius corresponds to higher mean value.

There are many holes and a blank band in the intensity map. Holes are often caused by instrumental problems. In more than 300 tiles FUV information is lost in this way. In the observation, bright sources are avoided, which contributes to the blank band and some other holes.

I want to get the background intensity of the sky, so some especially bright points(which is actually some big galaxies or supernovae) should be removed.

6. Conclusion

I have theoretically proved that it's possible to build a small space telescope for UV transient detection by calculating the limit effective area of the detector of the telescope. According to my results, for near sky survey, an effective area of detector around $10cm^2 \sim 20cm^2$ can easily detect $10 \sim 100$ supernova shock break-outs, the number of SBs varying significantly with effective wavelength. Many small corrections are eliminated in these calculations, but the deviation is within acceptable range. Background noise of all sky is studied carefully. Using DIS data I have the conclusion that intensity distribution within one tile is almost uniform. Then I go on to the AIS data, replacing each tile with its mean value and then plot the all sky intensity map.

7. Method Summary

Parameters used in §*Effective Area*:

SN1987A: $t_{day} = 1, E = 1.34 \times 10^{51} erg, \kappa = 1, M = 14.67 M_{\odot}, f_{\rho} = 1, R_{*} = 0.337 \times 10^{13} cm, \Delta t = 1500 sec.$

SNLS-04D2dc: $t_{day} = 1, E = 1.44 \times 10^{51} erg, \kappa = 1, M = 8.9 M_{\odot}, f_{\rho} = 25, R_{*} = 6.016 \times 10^{13} cm, \Delta t = 1500 sec.$

And take $\lambda = 1516\mathring{A}[2267\mathring{A}]$, $\Delta\lambda = 268\mathring{A}[732\mathring{A}]$, $m_{\rm gal} = 25[24]$ and $m_{\rm bac} = 27.5[26.5]$ for FUV [NUV] range.

In my reproducing the light curve, I also try to get the S/N ratio so that to varify my results. Here below is my detailed discussion about it.

$$S/N = \frac{n_{SN} \times \Delta t \times A_{\rm eff}}{\sqrt{(n_{SN} + n_{gal} + n_{bac}) A_{\rm eff} \Delta t}} \tag{10}$$

Where $n_{SN} = \frac{f_{\lambda}}{hc/\lambda} \times \Delta\lambda$ in photon rates, with f_{λ} the flux in wavelength unit and $\Delta\lambda$ is the band width. Δt is the exposure time. $A_{\rm eff}$ is the effective area of the telescope. n_{gal} and n_{bac} represent the photon count rates of the host galaxy and the sky background($r/cm^2/s$). S/N will be calculated for the NUV and FUV.

The observational results are obtained by GALEX. So I just used the website `http://galexgi.`

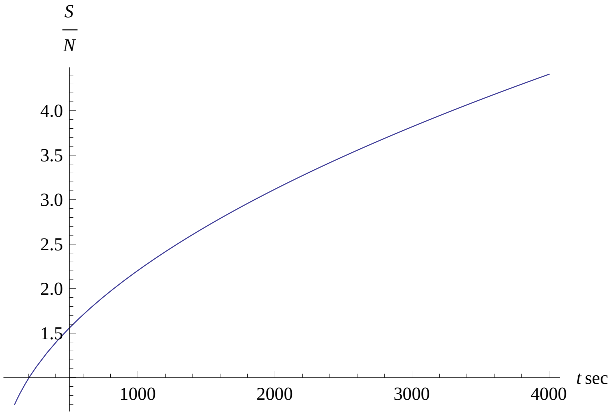


Fig. 19.— S/N as a function of time for FUV.

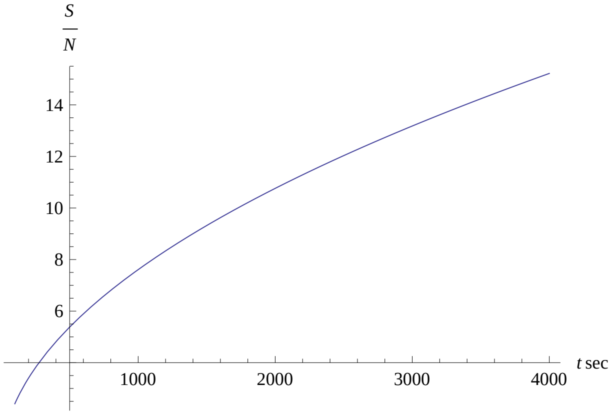


Fig. 20.— S/N as a function of time for NUV.

`gsfc.nasa.gov/docs/galex/FAQ/counts_background.html` for the conversion between GALEX count rates(n), fluxes(f), and AB magnitudes. The conversion can also be done by applying

$$n = f_\lambda \times \lambda/(hc/\lambda) \tag{11}$$

Accroding to `http://galexgi.gsfc.nasa.gov/docs/galex/Documents/ERO_data_description_2.htm`, I took $\lambda = 1516\mathring{A}$, and $\Delta\lambda = 268\mathring{A}$ for FUV calculation, and $\lambda = 2267\mathring{A}$ and $\Delta\lambda = 616\mathring{A}$ for NUV calculation.

The area of the host galaxy can be roughly estimated using Fig.5.(from Schawinski et al. (2008)), I took it as $Area = 3arcsec^2$.

The $n_{\rm gal}$ can be obtained in Fig.3 of Gil de Paz et al. (2007). The magnitue of WLM, NGC7808,UGC00017,PGC00282 are plotted as functions of radius, and it turns out that the magnitudes are mainly within the range of $24 \sim 28 mag/arcsec^2$ and $FUV - NUV \simeq 1$. I took 27[26] as the FUV[NUV] galaxy backgound for the calculation. The results are $n_{\rm gal}A_{\rm eff} = 3.4 \times 10^{-3} r/cm^2/s$ for FUV band and $n_{\rm gal}A_{\rm eff} = 36.6 \times 10^{-3}(r/cm^2/s)$ for the NUV band.

The $n_{\rm bac}$ can be estimated using Table 2 of Gil de Paz et al. (2007) and also Martin et al. (2005).The Table 2 of Gil de Paz et al. (2007) gives the FUV/NUV sky background for nearby galaxies observed by GALEX. But the host galaxy of SNLS-04D2dc is not included, so I looked up the location of this host galaxy and took the mean background value of galaxies in roughly the same direction as its background. In this way, for FUV, $n_{\rm bac}A_{\rm eff} = 1.7 \times 10^{-4}(r/cm^2/s)$, and for NUV, $n_{\rm bac}A_{\rm eff} = 2 \times 10^{-3}(r/cm^2/s)$. In Martin et al. (2005), it gives typical levels of $27.5[26.5] magarcsec^{-2}$ for FUV[NUV] sky backgrounds. That corresponds to FUV : $n_{\rm bac}A_{\rm eff} = 2.14 \times 10^{-4}(r/cm^2/s)$ and NUV : $n_{\rm bac}A_{\rm eff} = 3.66 \times 10^{-3}(r/cm^2/s)$. As can be seen, because $n_{\rm gal}$ is always about 10 times larger, these two methods give roughly the same results. I adopted the first one to give the following S/N.

The $n_{\rm SN}$ is calculated using the flux I already got. Because f is a function of $t_{\rm day}$, $n_{\rm SN}$ is not fixed (Fig.5& 6). But I can simply take an average as an estimation. In this case, I took $n_{\rm SN}A_{\rm eff} = 6.5 * 10^{-3}(r/cm^2/s)$ for FUV and $n_{\rm SN}A_{\rm eff} = 40 * 10^{-3}(r/cm^2/s)$

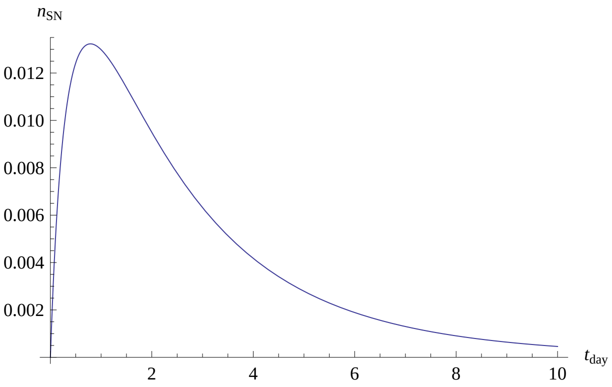


Fig. 21.— $n_{\rm SN} \times A_{\rm eff}$ as a function of $t_{\rm day}$

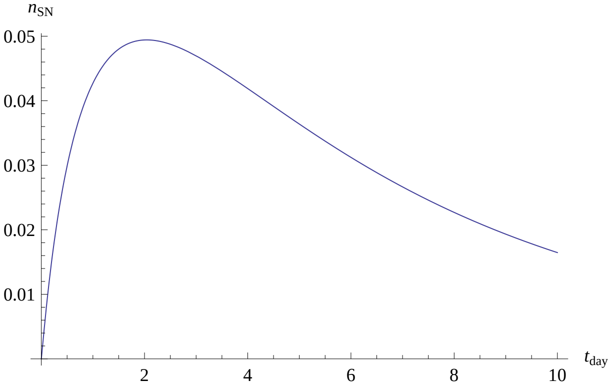


Fig. 22.— $n_{\rm SN} \times A_{\rm eff}$ as a function of $t_{\rm day}$

For a typical exposure of $t = 1500sec$, the FUV $S/N = 2.52$ and the NUV $S/N = 5.52$ are obtained. Judging from the error bars of the observational results, for FUV, $S/N \simeq 3$ and for

NUV, $S/N \simeq 7$. Considering the $n_{\rm gal}$ and the $n_{\rm bac}$ I used are just some very rough estimations, the S/N I got is good enough.

Fig. 23.— The *Hubble Space Telescope* F814W-band image of the host galaxy from the COSMOS survey.(Schawinski et al. (2008))

Data used in diffuse background analysis is the intensity map of each tile. The intensity map is generated by dividing the count map by the relative response map. The units are in count/pixel s.

The all-sky intensity map is plotted in this way so that the distribution of all sky can be read out very clearly and easily. Also, I give different size to different mean-value point so that some comparatively bright points can been seen more easily. This intensity map does not include all the information I got during my data analysis because both the color and the size of the marker point change discretely. If you want more detailed information, please email me via `ivyzhang13@gmail.com`.

In the data analysis, I used `ftp://galex.stsci.edu/GR4/pipe/02-vsn/` to retrieve objective data. Manual QA data is also retrieved to get the coordinate of each tile.

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