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Lower orphan afterglow rates for Gaia and LSST

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Gamma-ray bursts are high energy transients accompanied by their afterglows produced in relativistic shocks. The outflow is often highly collimated into a narrow jet. If the jet's symmetry axis is not pointed towards the observer due to relativistic effects the observer can not detect radiation from this beaming cone, but later on, in the afterglow phase the relativistic beaming of the jet becomes less significant, and the jet might be visible in the optical/radio bands. These bursts (the promp γ-emission is not detected, only the afterglow) are the so-called orphan GRBs. In this work we predict the rate of orphan-to-not-orphan bursts for the Gaia and LSST sky survey programs: our results suggest lower rates by $\sim$3 times for LSST and $\sim$9 times for Gaia.

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1. Introduction

There are theoretical considerations that gamma-ray bursts (GRBs) produce highly relativistic outflows into a narrow jet ([1]). When the ejected material encounters the circumburst medium of the progenitor synchrotron radiation is produced observed as an afterglow. The case when the burst is viewed off-axis and only the afterglow is detected is called an orphan-afterglow observation ([2, 3]). Detection of such bursts would constrain the ratio of orphan to not-orphan bursts. In this article we make a prediction for the orphan afterglow rate using the observational strategy of the Large Synoptic Sky Survey ([7]) and the Gaia satellite.

2. Simulations

The simulation of GRB afterglows was carried out with the numerical code BOXFIT developed by Hendrik van Eerten ([4]). The input parameters of the afterglows were chosen according to their observed or theoretical distributions. The initial jet half opening angle (θ_0) was chosen from the range $\sim 3° - \sim 28°$ and we applied two different types of distributions: a uniform ($P(\theta_0) \propto \cos(\theta_0)$) and a power-law ($P(\theta_0) \propto \theta_0^{-1}$) distribution. The redshift varies between the values of 0 and 10, the type of the distribution is taken from Wanderman et al. 2010 ([5]).

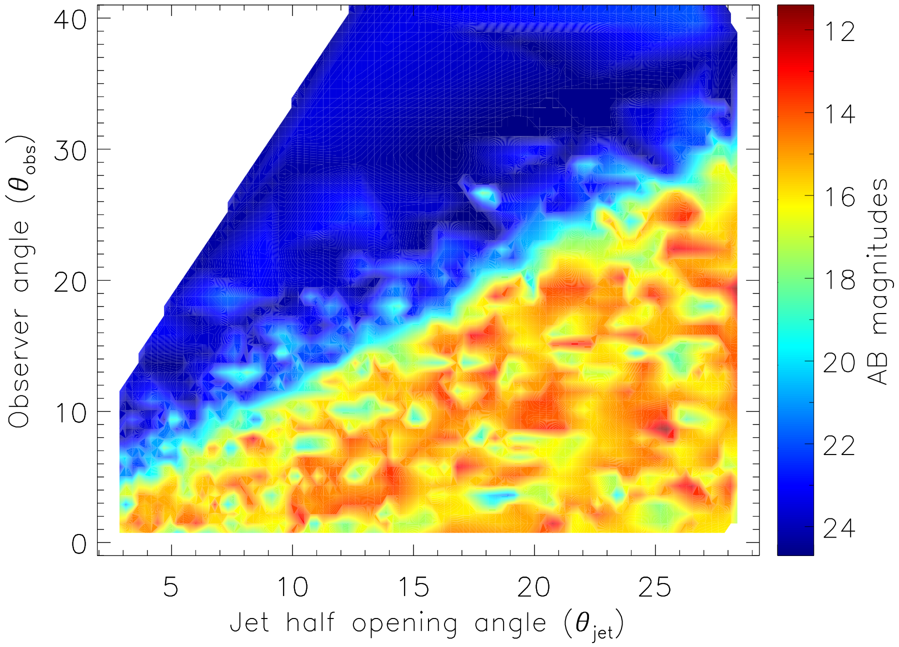


Figure 1: This contour plot shows how the peak magnitude of the afterglows correlate with θ_0 and θ_{obs} when $P(\theta_0) \propto \theta^{-1}$. As it can be seen the peak magnitude sharply drops when θ_{obs} becomes larger than θ_0. This is the consequence of the fact that the energy remains enclosed inside the initial opening angle of the jet. Taken $P(\theta_0) \propto \cos(\theta)$ the result is almost identical.

3. Intrinsic rate of GRBs

We assume that the intrinsic rate of GRBs follows the one determined by Nakar et al. (2002) ([6]). According to their results, the BATSE detection rate of long bursts with $\theta_{\rm obs} < \theta_0$ is 667 GRB/year. In order to determine the expected ratio of orphan to not-orphan GRBs ($N_{\rm on}$), we generated $\theta_{\rm obs}$ and θ_0 pairs and then counted the cases where the observer angle is smaller (or larger) than the initial jet half opening angle ($\theta_{\rm obs} < \theta_0$ or $\theta_{\rm obs} > \theta_0$):

- $N_{\rm on} \approx 5.33$, if $P(\theta_0) \propto \theta_0^{-1}$,
- $N_{\rm on} \approx 3.88$, if $P(\theta_0) \propto \cos(\theta_0)$.

4. General results

First, regardless of any sky survey program, we determined how the afterglows' peak brightness depends on θ_0 and $\theta_{\rm obs}$, it is shown on Fig. 1: the farther the observer from the jet symmetry axis, the lower the brightness of the afterglow.

5. Orphan afterglows - *LSST*

The telescope will cover the observable sky from it's site ($\sim$ 10000 deg^2) every three days ([7]), thus, the probability that a light curve will be observed by the *LSST* equals 1 if an afterglow will be brighter for at least 3 days than the *LSST*'s detection limit in any band. Based on simulations the bandpass r is the most suitable for observing GRB afterglows in case of the *LSST*.

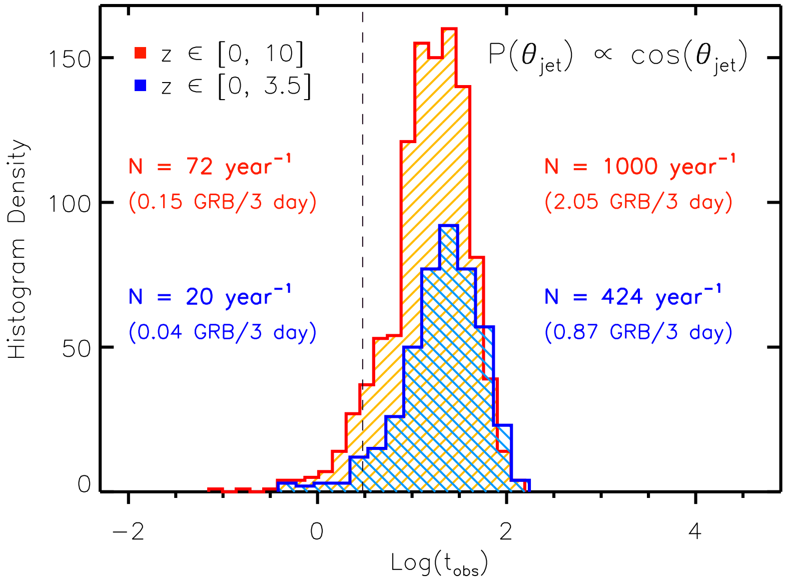
Considering afterglows both with uniform θ_0 and power-law θ_0 distribution case from the redshift range $z \in [0,10]$ and applying all of the observational constraints the *LSST* will detect ~ 2 optical afterglows every three days (one *orphan* and one not-orphan). Taking into account the flux attenuation by the Ly-α absorption line shifting into the r band, i.e. making the cut in the sample at redshift $z \simeq 3.5$, the number of observable afterglows per three days reduces to $\simeq 1$ ($\simeq 0.5$ *orphan* and $\simeq 0.5$ not-orphan).

In Fig. 2 we show the histogram of the $t_{\rm obs}$ values (the time duration while an afterglow is brighter than the LSST'S detection limit) for the case when θ_0 has a uniform distribution ($P(\theta_0) \propto \cos(\theta_0)$). When plotting the afterglows' peak brightness against the redshift (Fig. 3) we can see that GRBs with higher redshift still could be detected because of their high brightness. The reason we can not detect such GRBs is that the interviening neutral hydrogen gas clouds attenuate the afterglows' flux, reducing the probability to observe them.

6. Orphan afterglows - *Gaia*

There are two requirements for an afterglow to be observed by *Gaia*:

1. its peak brightness has to reach 20 magnitudes, which is the detection limit of the telescope,
2. the celestial coordinate of a GRB has to lie on the scanning track of the telescope.



[h!]

Figure 2: The histogram shows the distribution of time intervals ($t_{\rm obs}$) while the afterglows have a flux level above the *LSST*'s detetction limit, θ_0 has a uniform distribution in this case (with power-law distribution the numbers are as follows: $1034+97$ and $444+27$ bursts/year if $z \in [0,10]$ and $z \in [0,3.5]$, respectively.) If $t_{\rm obs} \geq 3$, then the afterglows will be observed probability of 1. The colors represent the afterglow subsamples: the red histogram shows GRBs from the redshift range $[0,10]$, while the blue one corresponds to a more realistic model, where we take into account the effect of the Lyman-α absorption in the spectrum, i.e. considering afterglows only up to $\simeq 3.5$ (corresponds to the *LSST*'s r-band). The vertical dashed line separates the afterglows where $t_{\rm obs} < 3$ days and $t_{\rm obs} \geq 3$ days.

Considering only GRBs with power-law θ_0 distribution (4222 burst/year) 788 are bright enough to be detected by *Gaia*. Applying the scanning law only seven bursts is detectable, but the flux suppression of Ly-α systems towards the GRBs reduces this number further to **one** burst/year, which is *not* an orphan burst. This rate is significantly lower than those predicted by Rossi et al. 2008 ([8]): ≈8.8 GRB/year. As for the LSST we also plotted the $\theta_0 - \theta_{\rm obs} -$ peak magnitude variables on the contour plot for the Gaia system on Fig 4.

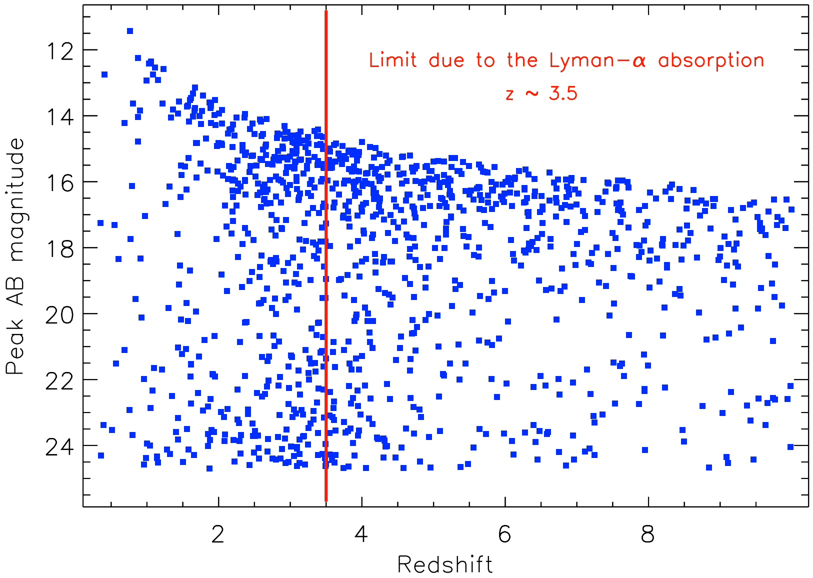


Figure 3: The figure shows the distribution of AB peak magnitudes in the r band against the redshift for light curves when $P(\theta_0) \propto \theta_0^{-1}$ for the LSST. As the redshift becomes higher, the peak brightness becomes lower. The reason we do not observe GRBs from high redshifts with 15-16 peak magnitudes is the flux suppression by the interviening neutral hydrogen gas clouds. The vertical red line indicates the redshift limit where the LSST's r-band filter overlaps the 1217 Å Ly-α absorption line, therefore, the afterglows start to fade because of the Ly-α forest suppression. The higher density of GRBs at $z \simeq 3.5$ is the result of the applied redshift distribution.

7. Conclusion

From the results above we can draw the following conclusions:

1. taking into account the Ly-α absorption by the interviening hydrogen systems the number of detectable afterglows reduces by a factor of two in the case of *LSST*, and this number changes from seven to one when observing with *Gaia*
2. the distribution type of the initial jet opening angle (θ_0) is almost irrelevant,
3. similarly, calculations with uniform and log-uniform burst energy distributions give comparable results,
4. *LSST* will detect **one** *orphan* and **one** *not − orphan* afterglows every three nights,
5. *Gaia* will detect **one** afterglows every year.

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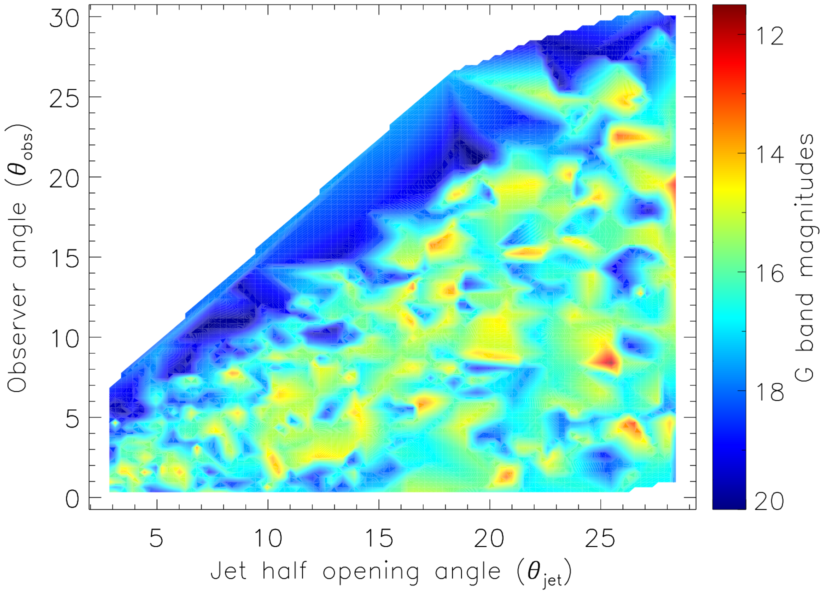

Figure 4: The contour plot shows how the maximal brightness of afteglows detectable by *Gaia* depends on the observer's angle (θ_{obs}) and initial jet half opening angle (θ_0). It is clearly seen that if the observer is inside the cone of the jet the peak magnitude can be higher. As soon as $\theta_{obs} > \theta_0$ the peak brightness sharply drops, and the afterglow becomes undetectable.

References

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