The estimation of detectability of on-axis GRB optical afterglows with Gaia

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With the launch of the Gaia satellite, a detection of many different transient sources is possible, one of them being optical afterglows of gamma-ray bursts (GRBs). With the knowledge of the satellite's dynamics and properties of afterglows one can make a simulation in order to estimate an average GRB detection rate. In the following sections, we first give a short statistical GRB optical afterglow overview and the basics of Gaia dynamics. We continue with the simulation description and its results.

1 Statistical properties of afterglows

Since the launch of the Swift satellite in 2004 a large number of GRBs and their afterglows has been detected. The Swift detection rate is about 100 GRBs per year. In about half of the detected GRBs there is no optical afterglow detected. Since the satellite covers approximately $\frac{1}{6}$ of the sky, we can estimate that there are around 300 GRBs per year, for which an optical afterglow could be detected. We emphasize, that only on-axis afterglows, i.e. those with their jet cones turned in our line of sight, are taken into consideration here.

We looked for the observations published in Gamma Ray Burst Coordinate Network Circulars [1]. We chose GRBs detected between Sep 2006 and April 2009 which had an optical afterglow detected (and reasonably well sampled) at approximately 0.01 day after the prompt GRB trigger. Our sample includes 100 GRBs.

In general, GRB optical afterglows follow a power law decay, $F_\nu \propto t^{-\alpha}$, with typical values of temporal decay index α lying between 0.4 and 1.4. For our purposes we take the average value of ≈ 0.7. Those values correspond to the time before a jet break (if there is a break at all). Usually the break occurs at later times, when the optical afterglow is already much fainter and harder to detect.

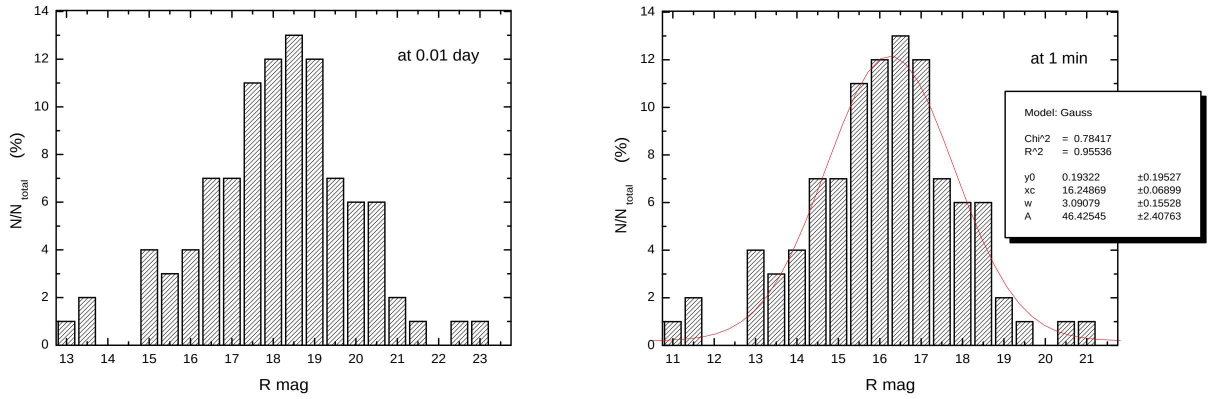
Magnitudes of optical afterglows at a given time can have a range of values. For our sample, the distribution of observed R magnitudes at 0.01 day after the prompt GRB is shown in Figure 1*a*; the same distribution shifted to 1 min after GRB trigger is shown in Figure 1*b*. Here we used previously mentioned average temporal index $\alpha = 0.7$ to calculate the change in magnitude through time:

$$m(t_2) = m(t_1) + 2.5\alpha \log\left(\frac{t_2}{t_1}\right). \tag{1}$$

We find that the distribution of magnitudes at 1 min after the GRB trigger is well described by the normal distribution with the mean value $\mu = 16.2$ mag and standard deviation $\sigma = 3.1$ mag. We will use this function later in our simulations.

2 Gaia dynamics

For the purpose of our simulation, the way Gaia will scan the sky is of crucial importance. Gaia carries two identical telescopes, separated by the angle of $\beta = 106.6°$ as shown in Figure 2. The satellite will make four rotatations per day around its axis (which is perpendicular to the direction in which both



(a) (b)

Figure 1: Number of observed GRB afterglows vs their R magnitudes at (a) 0.01 days and (b) the same data shifted to 1 min after the GRB trigger. Data obtained from GCN Circulars.

telescopes are pointing) with the constant angular velocity ω. The direction of the axis itself is tilted by the angle $\gamma = 45°$ from the direction of the Sun. The axis will experience slow precession motion around the Earth-to-Sun direction with a period of 63 days (Ω in Figure 2). Gaia will have an orbit around L2 point and will thus expirience rotation around the Sun, which is also shown in Figure 2. Knowing $\omega, \Omega, \gamma, \beta$ and one year period rotation around the Sun, one can construct the scanning law Gaia will obey.

The telescopes will have a field of view of $0.7 \times 0.7°$ each. The expected limiting R magnitude is ~ 20 mag.

There will be 9 CCD cameras on the focal plane of Gaia [2] [3]. Each source will be observed by each of them with 4.4 seconds integration time.

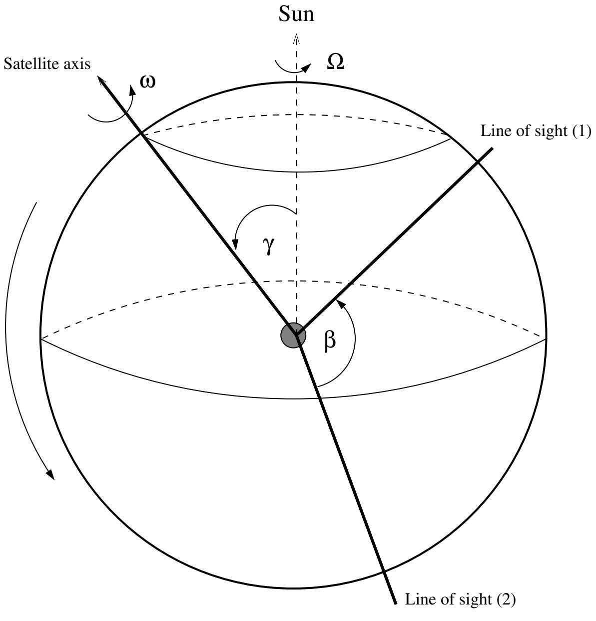


Figure 2: Sketch, showing how Gaia will scan the sky.

3 Simulation

The occurance of GRBs in the sky is random, meaning we don't know where or when to look for them. In chapter 1 we estimated, that there are around 300 GRBs per year, for which an optical afterglow could be detected. Following that, we generate 300 GRB bursts distributed randomly (but uniformly) over the sky and randomly (but uniformly) in time over the one year period. The magnitudes of generated GRB afterglows at 1 min after the initial trigger are distributed according to the normal distribution already discussed in section 1. We assume that the magnitudes are, according to (1) and assuming $\alpha \approx 0.7$, evolving with time as:

$$m(t) = m(1\ \text{min}) + 1.75 \log\left(\frac{t}{1\ \text{min}}\right). \tag{2}$$

Since the distribution of GRBs is random both in space and time, we do not have to specify a special initial position of the telescope's axes. We simply put the first telescope (number (1) in Figure 2) at the origin of fixed coordinate system at time $t = 0$ and from there on compute the position of the telescope's axis at time $t \neq 0$ according to the scanning law.

After we generate a GRB, we first calculate the time t_{lim} after which the GRBs magnitude will fall below the limiting magnitude. Then we check, where the positions of both telesopes are 1 min after the GRB burst, i.e. if they are pointing in the direction of a GRB. If they are not, we calculate the telescopes's axes path over the sky. We stop the simulation when the time t_{lim} expires and check if there were any detections with the first or second telescope. After that, the axes of telescopes are returned to the initial position, another GRB is generated and the described procedure is repeated.

We ran the simulation for a case of five years, which is the expected operational time of Gaia, corresponding to approximately 1500 GRB events. After that, the simulation was repeated for 1000 different sets of random numbers. All final results are then presented as an average over 1000 simulations.

4 Results

We did a simulation following the procedure explained in section 3. First we give results in the case of $M_{\text{lim}} = 20$ mag. The random generated magnitudes 1 min after the initial trigger are distributed according to the normal distribution as is shown in Figure 3a.

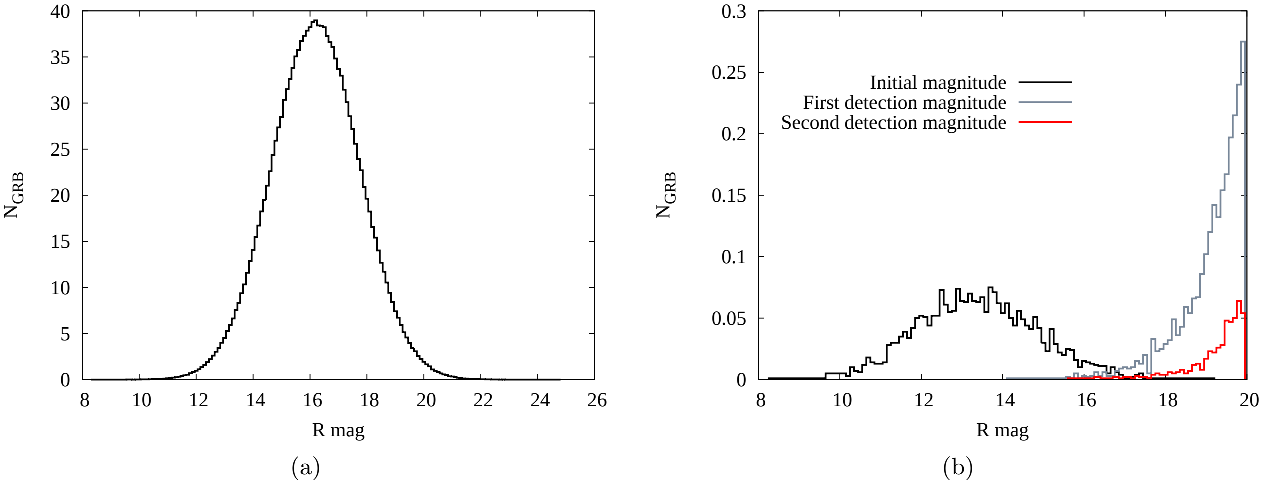
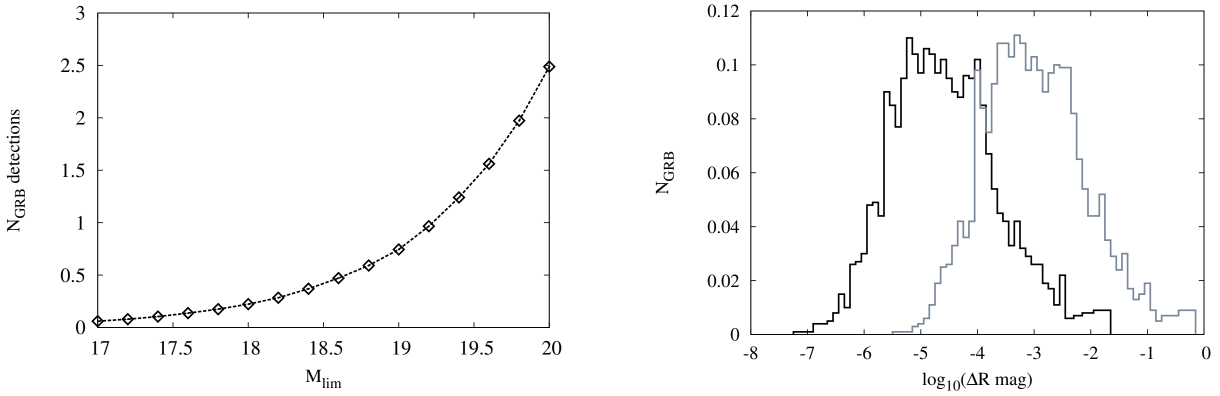


Figure 3: (a) Distribution of random generated magnitudes 1 min after the GRB trigger. (b) Distribution of magnitudes, which are associated with detected afterglows (black), same magnitudes at the time of the first detection (grey) and magnitudes of afterglows detected by the second telescope (red). The results are given for a five year simulation.



(a) (b)

Figure 4: (a) The average GRB afterglow detection rate in five years. (b) Distribution of the change in magnitude in 4.4 s (corresponding to an observation with 2 successive CCDs) (black) and the change in the time in which an afterglow is in the field of view (grey).

The distribution of initial magnitudes of optical afterglows, which were actually detected by the first (or second) telescope, is given in Figure 3*b*. It is also a normal distribution with the mean value ~ 13.5 mag. That is expected, since the afterglows with brighter initial magnitudes have more chance to be detected (their $t_{\rm lim}$ is longer). It is interesting to see the distribution of magnitudes at the time of their first detection (grey distribution in Figure 3*b*). Since the majority of detected afterglows are already quite faint, we can not expect many of them to be detected by the second telescope. Indeed, the distribution of twice detected afterglows shown in Figure 3*b* in red tells us, that only a small fraction of the afterglows can be detected with both telescopes.

The above results manifest themselves in the average GRB detection rate. In Figure 4*a* we show the number of GRBs detected by Gaia in five years for different limiting magnitudes. The results are not very promising. Even in the most optimistic scenario with $M_{\rm lim} = 20$ mag, one could on average expect to see only a few afterglows in five years. The probability to observe one with both telescopes is thus very small.

Since GRB afterglows are initially rapidly fading and they will be observed for 4.4 seconds by each CCD camera, the change of magnitude in that time could in principle be observable. For all detected afterglows in our simulations, we therefore calculated the change of magnitude in 4.4 s, corresponding to observations by two successive CCDs, and also for observations lasting as long as a specific afterglow is in the telescope's field of view. The distribution of the change of magnitude for both cases is shown in Figure 4*b*. We calculated the changes only for the first afterglow detection since the probability of detection with the second telescope is small. The change of magnitude could be detected only if it was greater than the photometric error. The expected photometric errors, averaged across the sky, are given on the ESA's web site attributed to Gaia [4]. Since the error in the case of $M_{\rm lim} = 20$ mag will be 10 mmag at best (but probably greater), the chances of observing the change in magnitudes will be small.

If the afterglow was actually detected by Gaia, it could be recognised from it's color properties [3] [5]. It has been observed, that the color indices $(R - I)$, $(V - R)$ and $(B - V)$ of a sample of observed afterglows are roughly constant in the first 10 days of observation, i.e. their time evolution is negligible. This property could serve as a mean to recognise an afterglow and to distinguish it from other possible sources.

References

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