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GRB follow-up and science with THESEUS/IRT

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Abstract. The aim of the space mission concept *THESEUS* is to continue to collect and study the GRB events like *Swift*. It will allow us to study the early Universe. Moreover, it will offer us to study with unprecedented sensitivity GRB emission and to measure the redshift for the bursts with $z > 5$. In this work, we investigate the advantages of a optical and near-infrared telescope mounted on the same satellite that is triggered by the GRB like *THESEUS*/IRT. Afterwards, we investigate the possible future developments in the GRB science, first for the prompt phase and the for afterglow phase. We find that more than half of the sources detected by *THESEUS*, and will never be visible from a a ground-based telescope. Moreover, only $\sim 50\%$ of all observable sources are visible within one hour, i.e. $< 30\%$ of all *THESEUS* transient sources. A higher number of observable sources can only be achieved with a network of telescopes. *THESEUS* will permit to detect the NIR prompt phase of the longest GRBs, increasing the number of events studied from gamma-rays to the near-infrared from a handful of events studied up to now to $\gtrsim 10$ GRBs per year.

Key words. Gamma rays: bursts

1. Introduction

After 50 years since their discovery, Gamma-ray bursts (GRBs) are still one of the most fascinating research fields in Astrophysics. Indeed, they are the most energetic gamma-ray emitter known, and a ultra-relativistic laboratory for high energy physics, high-redshift environment, massive-star formation and, cosmology.

After the discovery that GRBs are not local but cosmological explosions (thanks to the *Bepposax* space observatory Boella et al. 1997) of massive stars (e.g., Hjorth et al. 2003), in the last 12 years, *Swift* (Gehrels et al. 2004) allowed us to further improve our understanding of GRB phenomena, thanks to *Swift*'s rapid and autonomous slewing capabilities, in combination with its highly sensitive X-ray telescope (XRT; Burrows et al. 2005) as well as its optical/UV telescope (UVOT; Roming et al. 2005). Today, about 50 to 70 GRB optical afterglows can be localized annually by *Swift*, with 30 to 40 having redshifts determined mostly by ground-based observatories.

However, *Swift* is far beyond its planned life, and yet many questions are open: How the GRB engine exactly works? Why the GRB afterglow emission is so different from case to case? Is there a unique class of GRB progenitor and how is the influence of the environment in their formation? Are long GRBs progenitors good tracers of star formations? In order to answer these and many other questions further studies are in order.

The space mission concept *THESEUS* (Amati et al. 2018) aims not only to continue to collect and study the GRB events like *Swift*, but to measure directly the redshift of GRBs at z >5. Thus, it will allow us to make use of GRBs to study the early Universe, in particular star formation rate and metallicity evolution of the interstellar and intra-galactic medium up to redshift ∼ 10, signatures of Pop III stars, sources and physics of re-ionization, and the faint end of the galaxy luminosity function. *THESEUS* will also provide unprecedented capability to localize the electromagnetic counterparts of gravitational radiation.

The number of expected GRBs triggers per year from the *THESEUS* high-energy instruments (SXI and XGS) varies from 387 to 870. By taking the average value, one could expect about 2 triggers per day. Following-up all the triggers systematically and providing the associated redshift estimate is the key in order to be able to have enough high-redshift GRBs to fulfil the mission requirements. The near-infrared (NIR) telescope IRT on *THESEUS* gives access to the early afterglow and the late prompt phase of GRBs in some cases, a poorly studied interval so far.

In the following sections, we will first investigate the advantages of a optical and near-infared telescope mounted on the same satellite that is triggered by the GRB. Afterwards, we investigate the possible future developments in the GRB science, first for the prompt phase and the for afterglow phase.

2. Comparison between THESEUS/IRT and other facilities

The sample of long GRB lightcurves collected in the studies of Kann et al., (e.g., Kann et al. 2017, 2010), showed that almost all (> 90%) the afterglows of GRBs observed to date within few minutes are brighter than $R \sim 21$. Assuming an optical to NIR spectral slope of $\beta = 0.7$, the $R - H$ color is ∼0.7 mag (AB system). In this way, we can use Figure 1 and conclude that that almost all (> 90%) the NIR

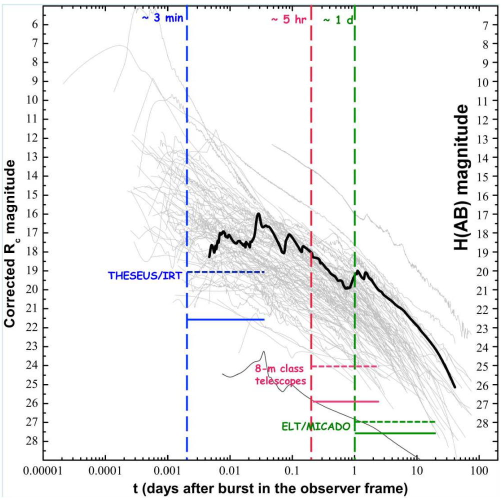

Fig. 1. Observed R band lightcurves of long GRBs adapted from Kann et al. 2017. The left axis indicates the H_{AB} magnitudes, obtained assuming standard afterglow color (see text). Highlighted is the ultra long GRB 111209A and the extremely extinguished GRB 130925A (bottom curve). Data is corrected for Galactic extinction. Adapted from Kann et al. (2017). We also show in the figure with blue lines the *THESEUS*/IRT sensitivity, the VLT FORS and X-Shooter sensitivity in red and, the ELT sensitivity in green (dashed line spectroscopy, solid line imaging).

afterglows of GRBs observed to date within few minutes after the trigger are brighter than H_{AB} ∼20, and they fade rapidly to $H_{AB} > 24$ within few hours.

Note that *Swift*/XRT, with an orbit and pointing constraints similar to what is planned for *THESEUS*/IRT, is capable to follow-up > 80% of GRBs. *Swift*/UVOT detects about 40% of afterglows (Roming et al. 2009), and it is limited by its size and the fact to operate in UV/optical, thus misses the most extinguished or $z > 4$ GRBs, all aspects that IRT will overcome. Even with these limitations, *Swift*/UVOT behaves better than any robotic ground-based telescope that recover only 20 − 30% of the afterglows (`http://www.mpe.mpg.de/~jcg/grbgen.html` and Greiner et al. 2011). Even if one considers the worst scenario of a GRBs detected close to the border of SXI FOV, IRT would be capable to detect all afterglows known to date and measure a photometric redshift for ∼ 90% of the cases (H_{AB} > 19.5), starting observing in LRS mode 20 min after the trigger (Amati et al. 2018; Götz & et al. 2018). This can be compared to a dedicated follow-up program on a 2m optical/NIR instrument like GROND mounted on the 2.2m ESO (La SIlla Observatory), which is capable to follow-up and detect < 20% GRBs within 30 minutes and 30% within 4 hours (Greiner et al. 2011), in agreement with what we find in section 3. Note that, assuming that $z > 6$ afterglows have IR luminosity and evolution similar to those observed up to date, > 50% GRB will have H_{AB} < 19.5 at 5 min after the trigger, thus they can be detected by IRT using LRS spectra and a photo-z can be measured. For the performances of IRT and the observing strategy of IRT see Amati et al. (2018) and Götz & et al. (2018). Finally, space observations are also not affected by sky absorption, which, especially at nIR wavelengths, makes large spectral intervals completely not accessible from ground thus affecting the spectral studies.

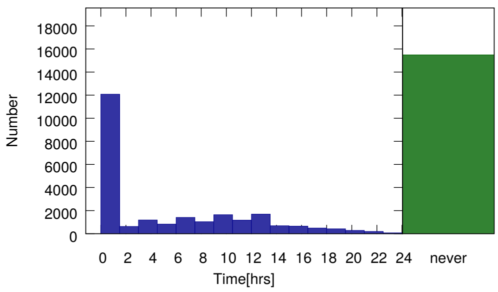

Fig. 2. *Left*: Distribution of the time on source TOS, i.e. the time needed before a transient source is visible from a ground observatory, in this case ESO Paranal Observatory (Chile). *Right*: Sources that are never observable from Paranal.

3. Ground-based follow-up of THESEUS triggers

The ground-based telescopes capable to reach a NIR sensitivity similar or better than IRT

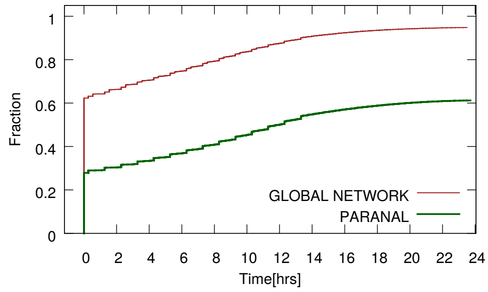

Fig. 3. Cumulative distribution of the time on source TOS. Observations from ESO/Paranal are in green. Observations from a global network of telescopes (red).

are larger than 2 m and are concentrated between Hawaii and Canary Islands in the northern hemisphere and between Chile and South Africa in the southern hemisphere. Thus, more than ∼ 30/50% of the northern/southern hemisphere is not visible for several hours from ground-based telescopes. At this time, half of the afterglows are bright enough only for the few 4 m or larger telescopes. Moreover, these telescopes are also limited by the impossibility to override other observations (i.e. time critical program running), which will likely happen (especially for ELT class telescopes and JWST) given that we expect to follow up more than 1 GRB per day.

In the following, we want to investigate the time needed by a ground-based observatory to be on source, i.e., the time on source (in the following: TOS). It is important to first notice that the IRT will be mounted on the same satellite where is the instrument devoted to be triggered by the transient. Thus, all triggers will be observed by IRT. The question, then, is how many triggers followed-up by IRT within a time interval (90 minutes, i.e., the *THESEUS* orbital period), can also be followed up by a ground-based observatory, and what is the TOS.

The ingredients to take in account depends from the observability of the transient which is given by:

i) the trigger time, given in UT;
ii) the time interval when the transient is above a given elevation limit (we have chosen 30° as this is an usual limit in

many observatories); it depends from the position on sky of the transient and the coordinates of the observatory;

iii) the start, end and length of the astronomical night at the observatory site (sun elevation > $-18°$), which depends from the coordinates of the observatory site.

The time spent before a transient is observable is the TOS.

Using the above ingredients, we have generated several thousands of sources triggered by a space observatory like *THESEUS* and calculated the TOS for a facility based on ground. The sources are uniformly distributed in the sky and their coordinates are in the intervals $0° < RA < 360°$,$-60° < DEC < 60°$. From these, we removed the sources too close in projection to the sun, i.e., those closer than 40°. This should be approximately the region on sky that will be more often covered by *THESEUS*, i.e. where it is more likely that a transient source will be. This is justified by the ±60° region on sky covered by SXI. We caution that this is just an approximation of the real case, because *THESEUS* real orbit will not be perfectly equatorial and its pointing will be constrained strongly by the Sun. We generated ~ 400 sources positions, and repeated the process for a observing time step of 90 minutes (approximately the duration of THESEUS orbit), during 24 hours and 4 times a year (i.e., summer and winter equinoxes and solstices), for a total of ~ 40000 sources. As typical observatory site, we have chosen the ESO/VLT at Paranal, which is good also for other international facilities in Chile (e.g., ELT, LSST, Magellan, GROND). Figure 2 shows the result of this simulation. Slightly less than half of the sources will never be visible from the site, and only ~ 30% of all sources are visible within one hour.

In order to maximize the number of triggers observable from ground, one would require a high number of robotic telescopes with NIR cameras in order to cover the entire Earth latitudes (at least every 45° in latitude) to cope with the day/night limitations and weather uncertaintie. Those robotic telescopes would need to be of the 2-4 m class in order to have an equivalent sensitivity to the IRT in space. Those facilities are not available to date, and it would require a complex international strategy to put them in place. We simulated a network of 6 sites which are already home of large telescopes and at very different longitudes to cover most of the world (ESO/Paranal, Hawaii, California, Arizona, Canary Islands, Xinglong/China). Figure 3 shows the cumulative distribution of TOS time for the global network and, for comparison, that for PARANAL. The global network allows to observe almost all IRT sources within 1 day, but only ~ 60% of IRT sources within one hour. However, it doubles what is achieved from a single observatory (Paranal).

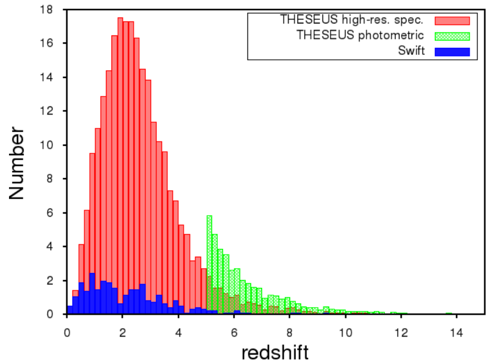

Fig. 4. The redshift distribution of *THESEUS* GRBs during a 5 yr mission lifetime compared to the actual distribution of *Swift* GRBs (blue) during the same period. GRBs with a photometric redshift are in green, and those with a spectroscopic redshift are in red.

4. Multiwavelength prompt emission

IRT will be capable to detect the NIR prompt phase of the longest GRBs (> 300 sec), increasing the number of prompt events studied from gamma-rays to NIR to 10 to 20 GRBs per year (Fig. 4 and Fig. 5). Today, they are limited to an handful of cases (Fig. 6).

Right now, thanks to *Swift*/UVOT and ground-based optical/NIR telescopes dedicated to the rapid follow-up of GRB afterglows, it is possible to simultaneously follow-up the prompt emission from optical to X-ray

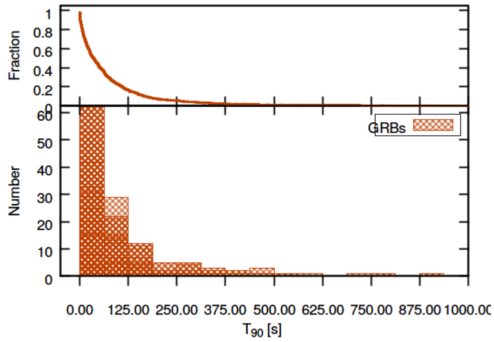

Fig. 5. Distribution of the T90 duration of *Swift*/XRT GRBs. Note that less than 10% of all GRBs have a duration longer than 300 seconds.

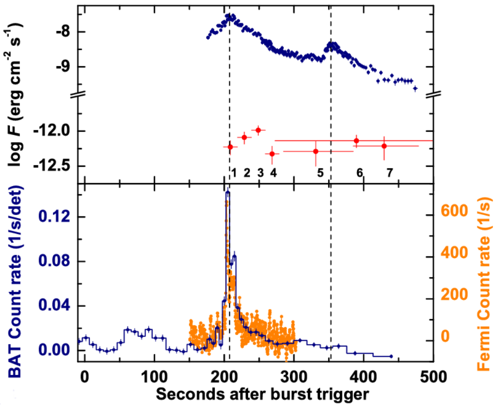

Fig. 6. Temporal evolution of the optical (red, top panel), X-ray (blue, top panel), and gamma-ray (bottom panel) emission of GRB 080928. The dashed vertical lines indicate the peak times of the two X-ray flares (adapted from Rossi et al. 2011).

to Gamma-rays. These observations allow us not only to better constrain the spectral energy distribution from optical to Gamma-rays and their lightcurves, testing the standard model, but also to test the nature of the central engine. Indeed, the observer may see simultaneously photons that have been emitted in different times and regions of the flow, and also with different physical origin, e.g., synchrotron or synchrotron self-compton emission. However, there are only a few tens of bursts in 12 years of *Swift* activity that could be long and bright enough to be detected in optical (Levan et al. 2014). Indeed, up to now only 6 events have been studied in such detail (Bloom et al. 2009; Rossi et al. 2011; Stratta et al. 2013; Elliott et al. 2014; Troja et al. 2017), and while they probe that standard fireball model can explain the observations, in some cases the optical and high-energy emission seems unrelated, or require a more complex modelling of the jet structure (see Fig. 6). Moreover, these observations have been performed in the optical, which is more affected by foreground and host line of sight dust extinction. With *THESEUS*/IRT capability of starting to obtain the first images within the first 5 min from the trigger, it will be possible to detect optical prompt emission for the longest GRBs, roughly 10 to 20 GRBs per year. This will dramatically increase the number of events to study, and allow us to statistically explore several models, shedding light on the structure of the jet during its first phases.

5. Complete samples

In order to study properties of GRBs, their X-ray and optical/NIR afterglows, and their hosts is important to handle a sample that is not biased towards classes (i.e. a complete sample), because of limitation during the observations. Until now, several GRB complete samples have being created (e.g., Greiner et al. 2011; Salvaterra et al. 2012; Perley et al. 2016). In addition to these, other tools to overcome the problems of unbiased distributions with robust and sophysticated statistical techniques have already been successfully applied to GRB prompt and afterglow emission (e.g., Dainotti et al. 2013, 2015). The capability of *THESEUS* to detect most afterglows in the IR, excluding the few highly extinguished or at extreme redshift ($<$ 10%), will allow us for the first time to build a complete sample of GRB afterglows observed in X-rays and IR. The fact that *THESEUS* will not be limited by weather conditions and visibility constraints, but only from pointing limitation and foreground Galactic extinction, is a strong advantage in respect to ground-based facilities dedicated to GRB follow-up (e.g. RATIR, GROND,REM).

6. Chances of misidentification

Minimizing the TOS will minimize the chances of wrong association of host galaxies. This is of fundamental importance in the case of short GRBs (sGRBs), which afterglow is much fainter then the long one (e.g., Kann et al. 2011) and often only a X-ray position is available. This is further complicated by the fact that the sGRB progenitor can travel several Kpc away from its birth site before to explode (e.g., Berger 2014). In the case of long GRBs (lGRBs), this often happens for those that are called dark GRBs, i.e. bursts which optical/NIR afterglow is dimmed by a combination of dust extinction and high redshift (e.g., Rossi et al. 2012). The recent finding of Perley et al. (2017) that the host of dark GRB 020819B was not a foreground spiral galaxy but a background high redshift galaxy is a clear example. The wrong host was often erroneously used as an unique example of GRBs host with high metallicity at low redshift, leading to a puzzling contradicting conclusions about the condition necessary to the progenitor of lGRBs to form. Another puzzling case is lGRB 050219A, which apparently exploded within a early-type galaxy, a unique case among lGRBs (Rossi et al. 2014), but the real host may be a smaller companion or background galaxy. More in general, Hjorth et al. (2012) estimates that up to 12% of lGRB-host association may be wrong. To minimize tha chances of a wrong host association, it is important to search for the host within a region that has to be as small as possible. Optical/NIR localization are better than X-rays, especially in the case of *THESEUS* (less than one arcsecond compare to several arcseconds). It is therefore important to minimize the TOS, and thus to detect the transient when is brighter, especially in the NIR, which is less affected by dust extinction and not affected by Lyman absorption up to redshift $z \gtrsim 12$.

7. Optical/IR afterglow detection with IRT

As shown in Figure1, within the first hour all known optical afterglows have $R < 22$. A classical optical afterglow has a spectral slope $\beta \sim 1$, which translates in a color $R - H \sim 1$ mag (AB system), thus within the first hour all known afterglows have $H_{AB} < 21$. IRT will observe optical afterglows longer than 30 min within 1 hour from the trigger (Götz & et al. 2018), reaching $H_{AB} \sim 20.6$. The optical/NIR imager GROND, reaching 1 mag fainter limits only, has been able to detect $\sim 90\%$ of all GRBs detected by *Swift* within 4 hours from the trigger (Greiner et al. 2011). Note that the host extinction will mostly have a negligible effect, with only a few cases ($\sim 10\%$) with $AV > 0.5$, which will noticibly dim (> 1 mag) the observed NIR afterglow when the redshift is $z > 4$, and still obtaining a detection rate of $\sim 90\%$. However, at these redshift dusty environments are less common, because dust did not have the time to accumulate in the star forming regions. Notably, the higher rate of *THESEUS* GRBs will allow us to better understand the shape of dust extinction curve at high redshift which is now unexplored, the presence of 2175 Å absorption in GRB SEDs in high redshift environments and to test different models for dust grains.

Compared to today, the larger number of *THESEUS* GRBs and the more sensitive spectra observed with XGIS will allow us to better understand the nature of the afterglow and of the central engine of GRBs. The study of the optical/NIR and X-ray afterglows unveils the properties of the environment. It is well known that the circum-burst density profile influences the shape of the GRB light curves and spectra (Racusin et al. 2009) distinguishing by ISM and wind environments (e.g., Schulze et al. 2011). Moreover, dust and gas on the line of sight dim the optical/NIR and X-ray afterglows. Their systematic study will unveil the properties of the environment where GRBs explode (e.g., Schady et al. 2012).

The X-ray lightcurves of GRBs are often show a slow fading plateau phase that can persist even longer than 10^4 sec (e.g., De Pasquale et al. 2016). This plateau phase is difficult to explain within the collapsar scenario, because it requires a long activity of the central engine. Alternatively, the necessary energy may come from the spin-down activity of a magnetar formed during the collapse (e.g., Zhang & Mészáros 2001). To complicate this view, X-ray flares (not visible in gamma-rays), probably due to late emission, indicate that the central engine is still active. Unfortunately, up to today the multi-wavelength study of these features has been limited by the different time coverage of X-ray and optical/NIR observations and sensitivity to the late afterglows. *THESEUS* will likely solve this problem thanks to the simultaneous observations of optical/NIR and X-ray afterglows.

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