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Gamma-ray burst studies in the SVOM era / Étude des sursauts gamma à l'ère de SVOM

The multi-wavelength context in 2015 and beyond

Le contexte instrumental multi-longueurs d'onde à partir de 2015

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ABSTRACT

We collect information as complete as possible about the upcoming telescopes and facilities relevant to gamma-ray bursts, both in the electromagnetic bands as well as for non-electromagnetic messengers. We describe the expected synergy between these new facilities and the SVOM mission and predict possible progress in the field of gamma-ray bursts over the next years.

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R É S U M É

Nous avons réuni des informations aussi complètes que possible au sujet des projets à venir de télescopes et expériences pouvant servir à l'étude des sursauts gamma, dans le domaine des ondes électromagnétiques comme pour les messagers non-photoniques. Nous décrivons la synergie escomptée entre ces futurs instruments et la mission SVOM et discutons les progrès à attendre dans l'étude des sursauts gamma au cours des années à venir.

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1. Introduction

SVOM will not only carry an X-ray and an optical telescope for GRB afterglow studies, but the ground-segment is also planned to incorporate an array of wide field-of-view optical cameras for the detection of prompt optical emission, plus two robotic 1-meter class telescopes for immediate optical/NIR follow-up observations of ECLAIR-discovered GRBs. With these new features it is interesting to investigate what synergy SVOM will have with the other planned space- and ground-based facilities. This exercise is attempted here, and we want to stress two caveats right from the beginning: (1) the selection of information has been done as careful as possible, but necessarily remains subjective; (2) history shows that most predictions of future (GRB) research results turned out to be wrong, or were dwarfed by unpredicted discoveries [1,2]. There is no reason to believe that this will not happen again.

2. Major successes in the field of GRB afterglows

The progress in the Gamma-Ray Burst (GRB) field over the last decade and prior to the launch of *Fermi* mostly occurred in our understanding of the afterglow emission and the GRB surroundings through the decisive measurements of *Swift* and

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enabled ground-based follow-up work. Classical observational astronomy, from radio to X-ray energies, played a vital role in this progress as it allowed the identification of GRB counterparts, thus drastically improving the position accuracy to the sub-arcsec level. Once the afterglows were identified, the full power of optical and near-infrared (IR) instrumentation came to play. This resulted in an overwhelming diversity of observational results and consequently in the understanding of the properties of the relativistic outflows, their interaction with the circumsource medium, as well as the surrounding interstellar medium (ISM) and the host galaxies. The number of well-sampled optical and X-ray afterglow light curves increased rapidly and revealed a surprisingly rich morphology. Observations of re-brightening and plateau phases, flares, and achromatic or chromatic breaks have become the norm and lead to adjunctions to the standard fireball model, such as multi-jet components, extended central-engine activity, and geometrical viewing-angle constraints. In addition, a long-lasting > 100 MeV emission detected in a handful of bursts by *Fermi*/LAT potentially revealed an extension of the external forward shock component over eight decades in photon frequency into the gamma-ray band [3].

Major progress happened in the field of high-redshift GRBs. While the highest redshift event at the time of the *Swift* launch was GRB 000131 at $z \sim 4.5$ [4], one year later the $z = 6$ barrier was broken with GRB 050904 [5], the QSO record broken with GRB 080913 at $z = 6.7$ [6], until GRB 090423 at $z = 8.2$ [7,8] established the absolute distance record for any cosmic object for about 1 yr (by now, a galaxy at $z = 8.56$ has been reported [9]). Systematic near-infrared observations have been recognized as crucial pre-requisite to identify high- z bursts, and two recently uncovered GRBs with photometric redshifts in the 9–11 range promise future progress on the GRB side.

Another field where the rapid GRB coordinate notifications by *Swift* had a particular impact is that of “dark GRBs”. Originally, these GRBs with X-ray afterglows but without optical detection (about 50%) were coined as “dark GRBs”. While more refined classifications of “dark GRBs” have been developed, the possibility of observing the afterglow within minutes with large ground-based telescopes has increased the detection rate to above 90%, thus allowing secure statements on the nature of “dark GRBs” to be made. Substantially more bursts with $A_V > 0.5$ mag are now revealed than in previous samples [10], and in many cases a moderate redshift (in the $1 < z < 4$ range) enhances the effect in the observer frame. The properties of this sample of early follow-up demonstrate that the darkness can be explained by a combination of (i) moderate extinction at moderate redshift, and (ii) an $\approx 20\%$ fraction of “dark GRBs” at redshift $z > 5$ [11].

The swift dissemination of GRB locations also lead to a significant increase of high-quality optical afterglow spectroscopy. Observations with large ground-based telescopes such as VLT/X-Shooter and Gemini/GMOS have become standard, and routinely provide redshifts and detailed views into the structure and chemical composition of the burst environs. With the launch of *Fermi*, and the exciting new discoveries with its two instruments LAT and GBM [12–16], some of the emphasis has moved “back” to the prompt emission characteristics.

3. Overview of upcoming facilities

In the next years before the launch of SVOM and during its operation many new missions and experiments will be brought online or reach their full potential. This list, presented in Table 1, is likely not complete, in particular not for 2015 and beyond, since national programs for both, ground- as well as space-based programs, can have a turn-around time of order 5 years. Thus, additional facilities are likely to emerge, many with strong synergy with SVOM. Advancements are expected in all areas of GRB research, from high-resolution X-ray spectroscopy, over thirty-meter-class optical and near-infrared imaging and sensitive all-sky radio monitoring to the exploration of new cosmic messengers (e.g., neutrinos, gravitational waves).

In the following, we describe the expected progress until the SVOM launch (Section 4), during the SVOM mission (Section 5), and end with a few topics where no progress is obvious, primarily due to missing instrumentation (Section 6).

4. Expected progress until the SVOM launch in 2015

4.1. Prompt emission

The interpretation of the parameters derived from the prompt emission has long been under debate because of the unknown correction for the redshift effect. With the advent of the simultaneous operation of *Swift* and *Fermi*/GBM there is now a growing sample of bursts for which both the redshift is measured via the optical/NIR afterglow, and the prompt emission characteristics are known beyond the 150 keV upper energy bound of *Swift*. While no results are yet published, the distribution of rest-frame properties will provide the first solid ground to test the assumptions made in the modeling over the past four decades.

This sample of common *Swift*/*Fermi* bursts is also expected to allow consistency checks on the bulk Lorentz factor Γ . In the gamma-ray regime, both the detection of tens-of-GeV photons as well as the variability of $> \text{MeV}$ emission allows to derive lower limits on Γ . In the optical, the early, rising part of the afterglow can be used to infer Γ . For this method, the redshift to a burst must be known, and the response after the GRB trigger needs to be fast (for $\Gamma \approx 1000$, the optical peak is expected only a few sec after the GRB).

Several bursts have been detected by the *Fermi*/LAT at energies above 1 GeV, including one short burst. Two of the three brightest LAT bursts (090510, 090902B), including the short burst, showed a clearly separate second spectral component on top of the usual Band-type simple broken power law. Whether this component is of leptonic or hadronic origin is widely

Table 1

Major ground and space-based facilities expected to be operational in 2015 and beyond.

Wavelength	Instrument	Start of operation	Area of impact
VHE γ -rays	HESS/MAGIC/VERITAS	2003	prompt emission mechanism; origin of high-energy component
	HAWC	2012	prompt emission mechanism; origin of high-energy component
	CTA	2016	prompt emission mechanism; origin of high-energy component
γ -rays	Fermi	2008	detection and localization
	SVOM	2015	detection and localization; broad-band afterglow spectroscopy
X-rays	Swift	2004	detection and localization; broad-band afterglow spectroscopy
	ASTROSAT	2011	broad-band (UV/optical to X-ray) afterglow spectroscopy
	NuSTAR	2012	hard-X-ray afterglow spectroscopy
	eROSITA	2013	detection of orphan afterglows
Optical	Astro-H	2014	high-resolution X-ray afterglow spectroscopy; chemical composition of environment
	HST	1990	late-time afterglows; host galaxies
	8–10 m telescopes	1999	all aspects of afterglows and host galaxies
	PanSTARRS	2009	detection of orphan afterglows
	Skymapper	2011	detection of orphan afterglows
	LSST	2015	detection of orphan afterglows
(Near)-IR	GMT/TMT/E-ELT	2018	afterglows of short-hard GRBs; GRB-SNe at $z > 0.5$; high- z afterglows and host galaxies
	Herschel	2009	host galaxies
	JWST	2015	high-redshift afterglows and host galaxies
Sub-mm	SASIR	2017	high-redshift afterglows
	MAMBO	2001	afterglows and host galaxies
	SPT	2008	afterglows and host galaxies
	SCUBA-2	2011	jet physics; host galaxies
Radio	ALMA	2012	high-redshift host galaxies
	LOFAR	2010	detection of orphan and triggered afterglows; jet physics, energetics
	EVLA	2010	afterglow observations; energetics and beaming
	MeerKAT	2011	afterglow observations; energetics and beaming
	ASKAP	2013	afterglow observations; energetics and beaming
Neutrinos	ANTARES	2008	explosion physics
	ICECUBE	2010	explosion physics
	KM3NeT	2014	explosion physics
Gravity waves	Advanced LIGO/VIRGO	2015	detection of gravitational waves from nearby short-hard GRBs

debated. One of the most prominent suggestions is a thermal origin in the photosphere of the fireball [17]. With the ongoing *Fermi* observations it will soon become clear whether this is a general feature, or occurs only in some bursts. In either case, it will have a profound impact on our understanding of how the prompt gamma-ray burst emission is produced.

4.2. GRB jet geometry and energetics

The degree of collimation and the observationally inferred prompt emission and early afterglow energetics are tightly connected. Collimation can be constrained in at least two ways, through observations of achromatic “jet breaks” in the X-ray and optical afterglow light curves and by comparing the number counts of on-axis GRBs and orphan afterglows. Only a small fraction of the *Swift*/BAT detected bursts has shown evidence for an X-ray or optical jet break [18]. Here, the general census is that *Swift* bursts are on average at larger redshift than the sample studied previously. Thus, their jet breaks occur typically at later times in the observer frame, at flux levels below the sensitivity of standard follow-up campaigns. Recent dedicated long-term afterglow monitoring with the more sensitive *Chandra* satellite succeeded in recovering jet break times for $\approx 40\%$ of the observed events [19]. Further progress requires even more late-time afterglow observations at optical and X-ray wavelengths.

A direct consequence of the collimated nature of GRB outflows is the prediction of orphan afterglows. These transients can arise when the initial GRB, and its associated afterglow light, are directed away from the observer. Here, the deceleration of the relativistic outflow, the associated decrease in special-relativistic beaming, and the hydrodynamic spreading of the collimated jet combine at the jet-break time, t_{jet} , to irradiate a fast-increasing fraction of the sky [20]. Observers illuminated during this transition will detect a steeply rising ($\Delta t \approx t_{\text{jet}}/10$) transient that proceeds to behave as a post-jet break, optical-X-ray on-axis afterglow. The substantial uncertainties in the GRB beaming fraction and in the redshift and luminosity distributions make rate predictions for wide-angle surveys difficult. However, observations in X-rays with *eROSITA* and optical wavelengths with e.g., Pan-STARRS, Skymapper, or LSST, are poised to uncover the first considerable sample of candidates.

The discovery of an orphan afterglow would serve also as a dramatic confirmation of the jet model for GRBs. At radio frequencies, afterglows are bright enough to be detectable even years after the burst. In particular, the orphan population detectable with LOFAR and later SKA will be dominated by several thousands of old GRB remnants (see Fig. 1). Such a large number of events would begin to map out the beaming distribution and, in addition, provide inputs to physical models of relativistic outflows. The late-time isotropic radio afterglow emission also holds the key to deriving the total burst energetics.

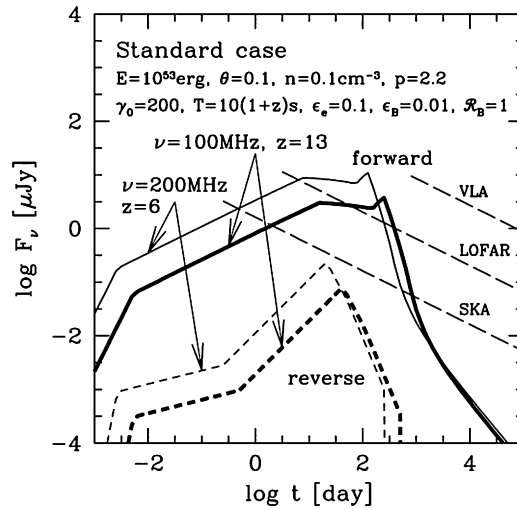


Fig. 1. GRB afterglow forward shock (solid line) fluxes as function of observed time at frequencies near the red-shifted 21 cm radiation for two redshifts ($z = 6, 13$). The $5\text{-}\sigma$ sensitivities for VLA, LOFAR, and SKA are indicated with long-dashed lines (from [21]).

This method has been successfully applied in the past, but limited to the brightest, typically near-by, events due to the low instrumental sensitivities. The upgrade of the VLA to substantially higher sensitivity (EVLA), and the starting operation of LOFAR and ALMA, the latter covering the peak of the synchrotron spectrum of GRB afterglows, will revolutionize the field. A significant fraction of, if not all, afterglows out to high-redshift will be detected and calorimetry will provide an unprecedented sample with well-measured energetics.

The question whether GRBs can be used as standard rulers has been discussed since the discovery of their cosmological origin. A number of γ -ray energy relationships have been proposed [22–24] and the most promising indicator has been identified as an apparently tight correlation between the peak energy of the GRB integrated prompt emission spectrum and the collimation-corrected equivalent energy (so-called Ghirlanda-relation [23]). The currently available event sample for which both quantities are well constrained is small. This is in particular the result of a poor overlap between the sample of bursts with accurately measured prompt-emission spectral parameters (mainly from *Fermi*) and the sample of events with well-localized afterglows (mainly from *Swift*) and jet breaks and redshifts. A slow improvement is expected from the increasing number of bursts detected by both, *Swift* and *Fermi* and by the increasing effort to identify afterglows of bright *Fermi* GRBs with ground-based optical wide-field images.

4.3. GRB fireball modeling

The evolution of the blast wave in the fireball model is governed by the total energy in the shock, the geometry of the outflow, and the density structure of the ISM into which it is expanding. The time dependence of the radiated emission depends on the hydrodynamic evolution and the distribution of energy between electrons and magnetic field [25]. The verification of the fireball model prediction concerning the broad-band SED is severely hampered by the presently low sensitivity in the sub-mm and mm bands which cover the peak of the synchrotron spectrum. Indeed, only a handful of GRBs have measured sub-mm/mm fluxes [26,27]. Moreover, the predicted movement of the cooling break is not seen in the majority of bursts, despite much better coverage of the optical to X-ray regime. A dramatic improvement in the sensitivity in the sub-mm to mm range is foreseen with the deployment of ALMA in Chile, in particular after the successful commissioning of the APEX instrumentation. The array will cover the range from 80 to 720 GHz, with a predicted sensitivity of $140 \mu\text{Jy}$ at 230 GHz and even better at lower frequencies. This should allow the detection and flux monitoring of a large fraction of GRB afterglows around the synchrotron peak, and in conjunction with the existing wealth of optical/NIR data, and the improved sensitivity in radio by EVLA and LOFAR enable the first systematic observational test of the fireball SED predictions. Moreover, it will also enable a good characterization of the sub-mm properties of many GRB host galaxies. Finally, another interesting possibility is that ALMA may be able to measure the redshift using molecular lines (e.g. CO, [CII] $158 \mu\text{m}$). [CII] $158 \mu\text{m}$ is the main coolant in the Milky Way, is much fainter in ULIRGs, and unknown so far in GRB hosts. With the ALMA high-frequency bands, a redshift range up to 8 will be covered.

4.4. Chemical evolution

Due to their brightness and large distance, GRB afterglows are complementing quasars as probes of the chemical evolution of the Universe. Rest-frame ultra-violet absorption lines provide important clues about the physical state of the intervening gas, its enrichment and dust content, and allow one to study directly the nucleosynthesis processes in massive

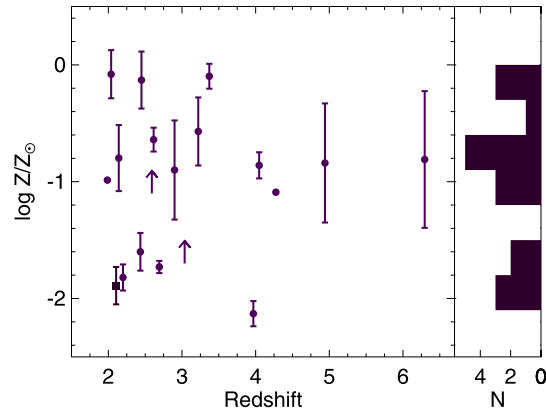


Fig. 2. Left: metallicities found in GRB DLA systems as function of redshift. Filled circles mark metallicities selected from the literature with arrows indicating lower limits (adopted from [29]). The filled square shows the position of GRB 090926A. The two points without error bars are for GRBs 030226 and 050505 for which no uncertainties for $N_{\text{H I}}$ have been reported. Right: metallicity histogram in bins of $\Delta \log(Z/Z_{\text{sun}}) = 0.3$. Lower limits have been excluded here. (From [30]).

star forming regions that host a GRB. The disadvantage of using GRB afterglows over quasars, however, is their transient nature. The fast fading, coupled with an a priori unconstrained redshift, can easily lead to a limited coverage of the important spectral features and diagnostics. In particular the access to the hydrogen column density is often limited due to the observational difficulty to measure it for objects at $z < 2 \dots 2.5$, thus complicating the abundance estimates.

A simultaneous coverage from the atmospheric cut-off to the near-infrared has become available with the installation of the intermediate-resolution ($R = 4000\text{--}14000$) X-Shooter spectrograph at the 8-m VLT in October 2009. Its routine use for afterglow spectroscopy now allows the detection of absorption and emission lines over the full wavelength range accessible from ground and promises to cover Damped Lyman- α systems (DLAs) and metallicity diagnostics more frequently. This is expected to lead to a steady increase of the number of well-sampled GRB sight-lines over the next years. The existing sample of ≈ 20 GRB DLAs (see Fig. 2) should be doubled until the launch of SVOM. By that time, in particular the sample of good-S/N spectra of high-redshift ($z > 4$) events will have significantly increased, and thus enhanced our understanding of the evolution of metallicity with redshift. Previous studies indicated that contrary to quasars sight-lines, GRB DLAs do not show a clear trend of decreasing metallicity with redshift [29,30]. However, the currently available sample of afterglow DLAs is dominated by sources in the redshift range of $2 < z < 3.5$ with very little coverage beyond that.

The increasing number of good-S/N spectra will also address the puzzling observation that MgII absorption systems intersecting GRB sight-lines appear to be stronger than their QSO counterparts [31,32]. The answer to whether this discrepancy lies in a selection bias or whether other factors (e.g., different MgII covering factors, weak gravitational lensing of an absorber population, or dust extinction bias) play an important role, will likely be concluded from the significantly increased sample of sight-lines.

5. Expected progress during the SVOM mission (2015–2018)

The scientific progress arising directly from the SVOM mission is described in Chapter 9. Arguably its most important contributions will be the burst alerts and the initial localizations of the optical and X-ray afterglows. At the point of this writing, it is uncertain whether the current burst flag ship *Swift* will still be operational in 2015. Thus, SVOM may carry the expectations for the whole GRB community for precise locations. The triggers and localizations will be crucial to maximally exploit the synergy between SVOM and the many experiments which will likely be operational during its mission time, in particular the new instrumentation commissioned after 2015 (see Table 1).

One of the pressing open questions in GRB research is that for the energy source of the ‘central engine’. The gamma-rays are produced at large distances from the central engine, and carry little information on the direct energy source. This is similarly true for the afterglow photons, though late-time flares have been used to argue for extended emission of the ‘central engine’. At least for short-duration GRBs, the detection of the gravitational wave chirp of the in-spiral phase (if the merger scenario is correct) by an advanced LIGO + VIRGO system (Fig. 3) offers a unique signature which will directly provide the masses of the two compact objects. Since the gravitational signal will also allow to deduce the luminosity distance, the prime energy release can be derived.

For long-duration GRBs, expectations are a bit more vague. Events in the very nearby Universe may produce detectable gravitational wave emission from the associated collapse, the black hole formation and the ring-down phase [33]. Similarly, the predicted neutrino signal of the explosion of massive stars within the Virgo cluster is in reach of the next generation of neutrino detectors (e.g., KM3NeT). Such bursts are rare, but if one could be detected, the neutrino signal would provide a very good proxy for the energy scale of the explosion, since practically all models predict that $\approx 99\%$ of the energy is carried by neutrinos. Another aspect of long-duration bursts is the claim, based on a handful of ‘special’ bursts, for a population

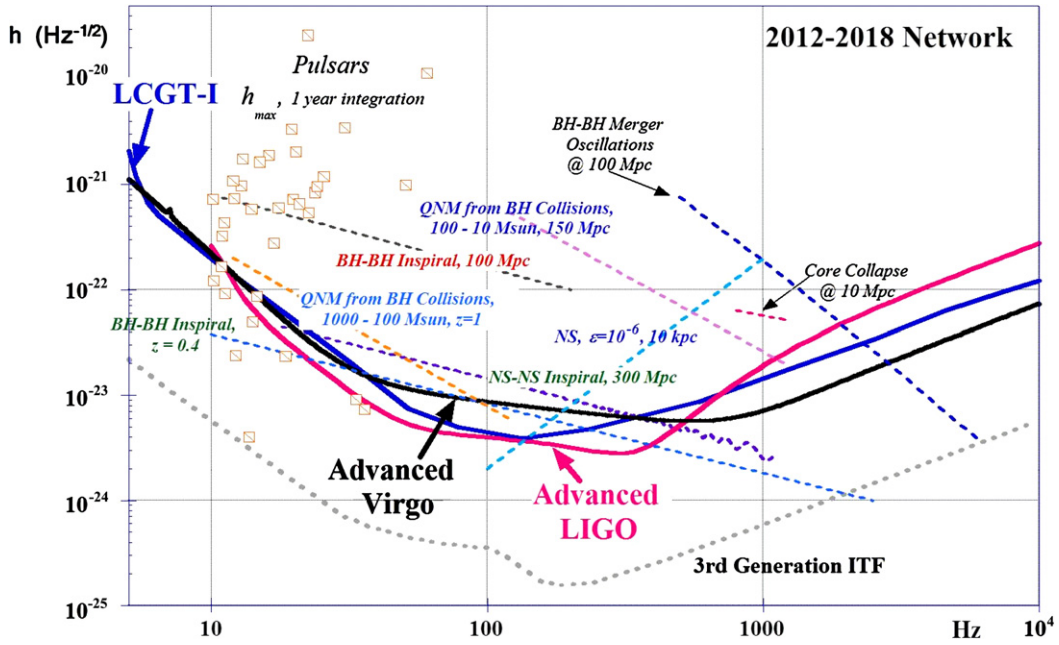


Fig. 3. Sensitivity of ALIGO for compact binary mergers. (From [28].)

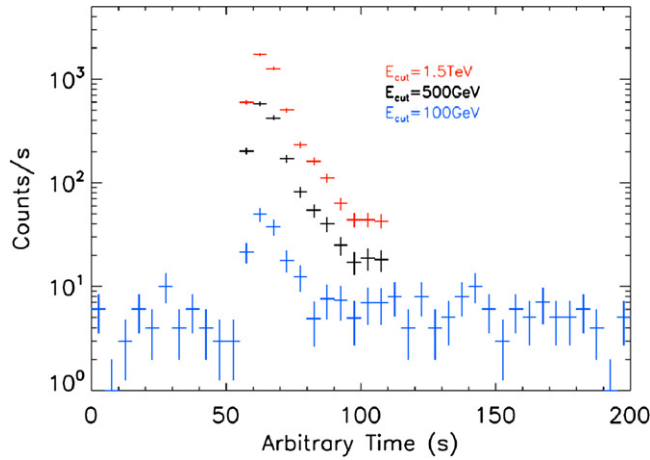


Fig. 4. Simulated HAWC signal for a GRB with a fluency of 1×10^{-4} ergs cm^{-2} , comparable to the 10 keV–10 GeV *Fermi* fluency of GRB 090902B, for three different cut-off energies. (From <http://hawc.umd.edu/science.php>.)

of nearby, low-luminosity GRBs rather than bursts seen off-axis [34,35]. While these bursts are very rare (SVOM might just detect one or two over its mission lifetime), they are particularly interesting since the small distance ($z < 0.1$) allows detailed studies of the associated supernova, the host galaxy and the location of the GRB therein.

The *Fermi* satellite has produced a wealth of new exciting results about the prompt gamma-ray emission (see Chapter 6). Most of these, however, were tightly linked to quantities derived from the multi-wavelength follow-up, in particular the redshift. With a likely overlap of both missions, SVOM will continue to provide precise localizations for GBM and LAT detected GRBs, thus enabling the crucial overlap between prompt and afterglow measurements.

Localizations by SVOM will also be important for the follow-up with the next generation of ground-based very-high energy gamma-ray detectors. The High Altitude Water Cherenkov (HAWC, [36]) experiment will surpass the sensitivity of MILAGRO by more than 15 times between 0.1 and 100 TeV, while offering a similarly wide field of view (2π) and duty cycle ($\approx 100\%$). These are essential characteristics to measure the prompt emission of GRBs (Fig. 4) and simulations indicate that HAWC will be sensitive to redshifts of $z \approx 1$. For more nearby events, hundreds of photons above 100 GeV can be detected, allowing HAWC to directly probe the bulk Lorentz factor and size of the emitting region. Even higher sensitivity will be reached with the Cherenkov Telescope Array (CTA, [37]), which, however, will require external event triggers due to its narrow field of view. The current design foresees a high mobility of a part of the array (180 deg in 20 s) allowing CTA to

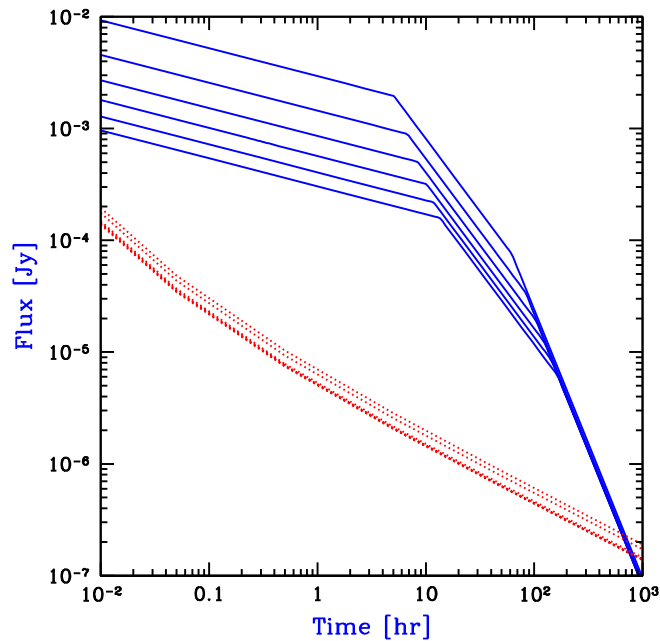


Fig. 5. JWST detectability of high-redshift GRB afterglows as a function of time since the GRB explosion. The GRB afterglow flux is shown (solid curves) at the red-shifted Ly- α wavelength. Also shown (dotted curves) is the detection threshold for *JWST* assuming a spectral resolution $R = 5000$ with the near infrared spectrometer, a signal to noise ratio of 5 per spectral resolution element, and an exposure time equal to 20% of the time since the GRB explosion. In each set of curves, a sequence of redshifts is used, $z = 5, 7, 9, 11, 13,$ and $15,$ respectively, from top to bottom. (From [38]).

quickly slew to SVOM burst locations and to cover part of the prompt emission and in particular the delayed high-energy component. GRBs with measured redshift will allow to study the effect of the optical-IR extragalactic background light (EBL) on the shape of the TeV spectra of GRBs at much better significance. The EBL directly relates to the early star formation, and is extremely difficult to measure otherwise. The present best constraints on the (UV) EBL are for GRB 080916C and 090902B from Fermi/LAT measurements of GeV emission.

Systematic near-IR follow-up on bigger ground-based telescopes (e.g., SASIR) and from space (e.g., *JWST*) promises to significantly increase the rate of high-redshift identifications. In particular the James Webb Space Telescope (*JWST*) will provide a crucial milestone in the study of the early Universe through GRBs. *JWST* is an infrared-optimized 6.6 m space telescope by NASA with major contributions from ESA and CSA. Its sensitivity will allow detailed IR spectroscopy of GRB afterglows even a week after the burst (Fig. 5). This will be unique in particular for GRBs at high redshift ($z > 8$) where ground-based spectroscopy is severely hampered by the sensitivity of present-day 8–10 m class telescopes. It will thus be crucial for SVOM to identify high- z GRB candidates rapidly, in order to provide feasible input to *JWST*. With the direct detection of Pop. III stars being impossible with *JWST*, and the possibility of detecting the supernovae related to the explosion of primordial stars getting slimmer, GRBs presently represent the best hope of pointing *JWST* to the first star(s).

Another aspect where improvements are expected is the regime of high-time resolution optical observations, both during the prompt GRB phase as well as in the early afterglow phase. In the past, high-time resolution (seconds or faster) optical/NIR follow-up has been obtained only occasionally and primarily on small, robotic telescopes [39,40]. While variations on 10-sec time-scales and below have been seen, with clear deviations from a smooth power-law decay, attempts to improve the experimental capabilities are very scarce. High-time resolution capabilities are currently discussed for implementation in E-ELT instrumentation and may have a huge impact in understanding the early afterglow physics.

6. Areas with no expectation for major progress in the next decade

We do not anticipate major observational progress on the question of what role a magnetic field plays in the central engine of GRBs. Optical/NIR polarimetry facilities exist, but over the last years there has been little dedication to use them, primarily because the wildly variable afterglows do not allow clear conclusions to be drawn on the possible jet structure and magnetization even if variable polarization is detected [41,42]. Similarly, X- and γ -ray polarimetry has been proposed, but the presently built or proposed small piggyback or balloon instruments do not promise a real breakthrough for the next decade, particularly time-resolved polarimetry over the burst duration and comparison with the polarimetric properties of precursors and late-time flares. The mission GRIPS [43], proposed to ESA in the Cosmic Vision program, would be able to measure time-resolved polarimetry over the burst duration, but even if selected by ESA, would not operate before 2020.

Another area of concern is the simultaneity of optical/NIR and X-ray coverage of the afterglow emission. During the early Swift mission, good optical coverage of the many exciting X-ray variability patterns was rare. With the advent of

dedicated and/or larger (semi-)robotic optical telescopes, the situation has reverted: many new features in the optical/NIR light curves have no coverage in X-rays. This could only be improved with an all-sky survey mission, possibly in the Lagrange Point 2, with a large field of view and sensitivity down to the sub-mCrab range. Similarly, more systematic late-time (beyond 3–4 days) X-ray observations would be useful to investigate the jet-break issue as well as the nature of the late-time optical bumps – the corresponding X-ray telescopes are available, but are not systematically used so far.

Even more interesting would be rapid high-resolution X-ray spectroscopy with large telescopes to solve the puzzle concerning the ionized absorbers and the WHIM, or attempt alternative redshift measurements. The presently available *Chandra* and *XMM-Newton* telescopes have too slow slewing times to allow a major breakthrough, and this will likely also be the case for the Japanese Astro-H mission. The missions GRAVITAS and ORIGIN (previously EDGE and XENIA) [44], proposed to ESA in the Cosmic Vision program, or DIOS [45], proposed to the Japanese Space Agency, are designed to have a rapid slewing capability, and thus would be able to perform these measurements; but even if selected, would not operate before 2020.

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