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Gamma-Ray Bursts: frontier astrophysics with the most extreme cosmic explosions

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This paper presents the main properties of Gamma-ray bursts (GRBs) and their connection with various topics of modern astrophysics. The future of the field is also addressed with a detailed presentation of the SVOM Sino-French mission and its scientific objectives.

Keywords: Gamma-ray bursts, Cosmology, Gravity waves

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1. Gamma-ray bursts

Gamma-ray bursts (GRBs) are powerful cosmic explosions produced at the end of the life of some massive stars, but also when two compact stars in a binary system merge after the dissipation of the angular momentum by gravitational waves. In both cases, the catastrophic event results in the birth of a fast rotating compact object (a black hole or a magnetar) which expels transient but very powerful relativistic jets in two opposite directions. If, by chance, one of these jets is directed towards the Earth, we observe a bright gamma-ray transient (the prompt GRB), which is followed by quickly fading afterglow emission at longer wavelengths (from X-rays to visible and radio).[1]

While the brightness of GRBs allows their detection out to very large distances (up to redshift z = 8.3 for GRB 090423 [66, 73]), we only detect the GRBs which emit a jet towards the Earth. Assuming an average opening angle of GRBs jets of a few degrees, the fraction of detectable GRBs amounts to 0.1 to 1%.

This paper is divided into two parts. Section 1 provides a brief overview of the GRB phenomenon including some *frontier topics* that may interest the participants of this conference. Section 2 contains a brief description of the instruments and the scientific objectives of the future GRB mission SVOM, that will perpetuate GRB detection after Swift. The reader interested in getting a complete view of the field and its recent advances is invited to read the reviews listed in the bibliography [22, 87, 23, 9, 38, 49]. The reader interested in an overview of the discoveries that have led to the solution of the so-called *GRB mystery* is invited to read the books of Vedrenne & Atteia [80] and of Kouveliotou, Wijers & Woosley [36].

1.1 Prompt emission

GRBs are *transient events* whose temporal evolution is divided into two steps: the prompt GRB and the afterglow. Figure 1 shows the main properties of the prompt GRB emission in hard X-rays: the light-curve of the bright nearby GRB 030329 at redshift z=0.17; the $\nu F\nu$ spectrum of GRB 100724B peaking around $E_{peak} \sim 500$ keV; the isotropic distribution of GRBs on the sky [6], and the duration histogram which shows two peaks suggesting the existence of two classes, respectively called short and long GRBs.

High-energy satellites play an essential role in the detection and classification of GRBs. The Large Area Detectors of *BATSE*, which have worked more than 9 years have shown that about 1000 GRBs cross the solar system each year (hereafter we call these bursts "classical GRBs", in contrast with X-Ray Flashes or low-luminosity GRBs described below). Since then, instruments like *BeppoSAX* WFC and *HETE-2* WXM have extended GRB detection to soft X-rays, revealing the existence of very soft GRBs ($E_{peak} \leq 30$ keV), which have been called X-Ray Flashes (XRFs) [31, 34, 5, 65]. XRFs are closely connected with GRBs, except for their E_{peak} and their fluence, which are 10-50 times smaller than regular GRBs. At much higher energies, the Large Area Telescope (LAT) onboard Fermi has detected GeV emission from several GRBs [61]. This emission is often attributed to the external shock [87], even if it is detected with high-energy satellites.

[1] According to a nearly 50-year tradition, GRBs are identified with the date of their detection on Earth followed with a letter indicating their rank within this day or with 3 digit indicating their time of detection as a fraction of a day, as an example GRB 141004A = GRB 141004973 is the first GRB detected on Oct. 4, 2014, at 23:21:00 UT.

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Rarely, a GRB detector is triggered by a nearby ($z < 0.1$) low-luminosity GRB (LL GRB). Assuming isotropic emission, low-luminosity GRBs radiate an energy which is $10^3 - 10^4$ times fainter than classical GRBs. While these bursts might dominate the GRB population, their connection with the population of bright classical GRBs is poorly understood.

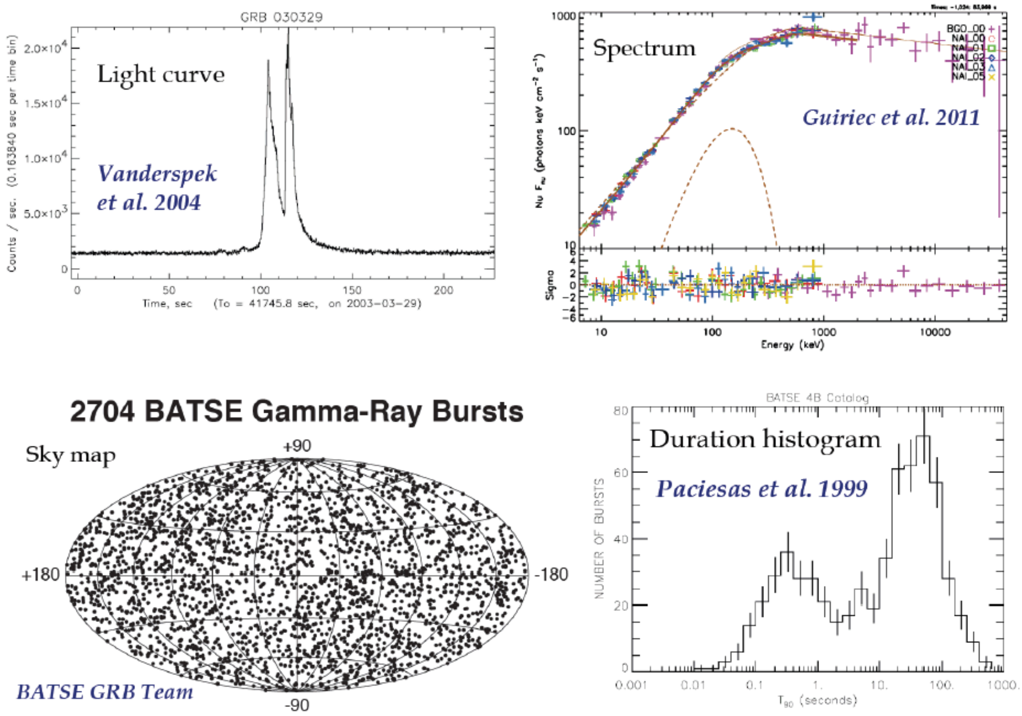

Figure 1: Some properties of prompt GRB emission. *Upper left:* Light-curve of the bright GRB 030329 in the range 7-400 keV [78]. *Upper right:* $\nu F \nu$ energy spectrum of GRB 100724B [29]. *Lower left:* All sky distribution of GRBs, showing their isotropy [6]. *Lower right:* Duration histogram of prompt high-energy emission with two maxima around 0.3 and 40 seconds, corresponding to long and short GRB populations [53].

1.2 Afterglow

After nearly three decades where only the prompt emission was detected, *BeppoSAX* permitted the discovery of GRB afterglows thanks to the distribution of arcminute positions within few hours of the burst [16, 79]. Then, *HETE-2*, *INTEGRAL* and *Swift* have set new standards, distributing arcminute locations within seconds of the GRB. With *Swift*, these positions reach a precision of several arcseconds, thanks to the localization of the X-ray afterglow with the XRT. The remarkable combination of sensitivity, speed and accuracy achieved by *Swift* for GRB localization has permitted measuring more than 300 GRB redshifts and host galaxies.

GRBs afterglows are visible at all wavelengths. They permit locating GRBs accurately, finding their host galaxies, measuring their distance and energetics, and studying the physics of GRB jets and the interaction of the jet with its environment. The location of *long GRBs* in star forming regions and the clear association of several nearby GRBs with supernovae appearing several days after the burst [20, 32, 70, for instance] have provided strong evidence that long GRBs are connected with the end of life of massive stars. The supernovae associated with GRBs are hypernovae (supernovae with large kinetic energy of the ejecta) of type Ibc (without hydrogen and helium lines), indicating that they had ejected their envelope before the explosion.

Short GRBs have faint afterglows, they are not associated with supernovae, and they occur in all types of galaxies. Their rate and their energetics are compatible with mergers of compact stars (two neutron stars or a black hole and a neutron star) as explained in section 1.4.

1.3 Relativistic outflows in GRBs

The huge brightness of GRBs and their extreme compactness imply an enormous photon density at the source, leading to a very high opacity to gamma-ray photons due to photon-photon pair creation (10^{12}!). In these conditions we should observe a thermal spectrum with a strong cutoff at 511 keV. This is not the case, since many GRB energy spectra are correctly fit with broken power laws extending to MeV energies or beyond. The solution to this apparent paradox lies in the relativistic motion of GRB outflows. When special relativistic effects are taken into account, the photon-photon opacity is reduced by a factor Γ^6, where Γ is the bulk Lorentz factor of the outflow (see for instance Piran 1999 for a review [58]). In order to solve the issue of GRB opacity to gamma-ray photons, it is necessary to consider GRB outflows moving at 99.995% of the speed of light, with bulk Lorentz factors $\Gamma \geq 100$). The relativistic motion of the outflow also boosts the apparent luminosity by a factor Γ^4 (Doppler boosting effect), explaining the observed luminosity of GRBs.

There are theoretical and observational reasons to believe that GRB outflows are not spherically symmetric, but collimated into two narrow jets ejected in opposite directions. Assuming typical beaming angles of few degrees reduces the energy budget of observed GRBs by 100-1000 (with respect to the energy computed assuming isotropic emission) and multiplies the number of sources by the same factor.

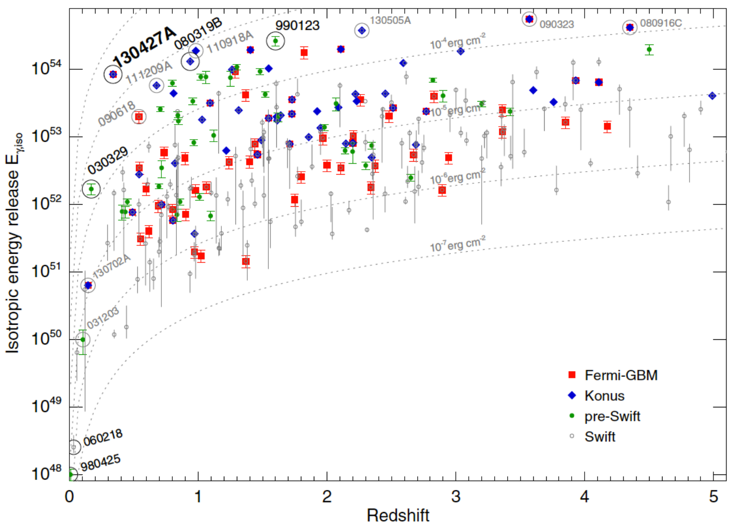

Figure 2: Isotropic energy release of GRBs as a function of their redshift [57]. Faint GRBs with $E_{iso} \leq 10^{51}$ erg are only detectable locally. GRB 980425 and GRB 060218 on the lower left part of the figure belong to the category of sub-luminous GRBs.

1.4 GRB progenitors

1.4.1 Long GRBs and low luminosity (LL) GRBs.

Long GRBs and LL GRBs are due to massive star explosions producing hypernovae with transient relativistic jets. The enormous energy released by these events appears in various forms: the kinetic energy of the hypernova, a large amount of Nickel 56, and a relativistic jet powered by a central engine active during several seconds. The energetics may be dominated by the jet (GRBs) or by the kinetic energy of the hypernova (LL GRBs). The presence of a jet in nearby hypernovae can be inferred with radio observations which trace the relativistic outflow, even when it is not directed toward us. The vast majority of Type Ibc hypernovae show no evidence of a relativistic jet, and it seems that at most a few percent of SN Ibc produce GRBs [7, 69]. This raises the question of the nature of the central engine and the conditions needed for its existence.

The association of GRBs with massive stars and the well-known ability of black holes to accelerate relativistic jets (in active galactic nuclei and galactic microquasars) have led to models explaining the production of GRBs by cores of massive stars which collapse into black holes. Numerical simulations have shown that the stellar core must have a large angular momentum to permit the building up of an accreting torus, and that, under some conditions, the jet accelerated by the black hole can pierce the stellar envelope and escape into space (e.g. [83, 86]). This model raises numerous interesting questions, which concern the physical processes at work close to the black hole and in the jet, the possibility to keep a large angular momentum in the stellar core while ejecting the envelope of the progenitor, the possibility of using the prompt emission to infer the nature and the properties of the central engine, the afterglow evolution which is most often successfully fit by a jet interacting with a constant density medium and more rarely with the stellar wind of a massive star, etc. These questions show that we are far from understanding the central engines of GRBs. For this purpose, it is essential to gather more information on GRB progenitors, to understand better the role of binarity and metallicity in the final fate of massive stars, and to clarify if short-lived magnetars or quark stars are formed during the collapse. Nearby GRBs play a crucial role in this quest since their associated supernovae and their host galaxies can be studied in detail.

1.4.2 Short GRBs.

Short GRBs are not associated with young massive stellar populations. Their occurrence in all types of galaxies, their lower energy output, and their rate are compatible with their origin in mergers of compact stars (binary neutron stars or a neutron star with a black hole). Their distance and frequency make them privileged sources of gravitational waves (GW) for advanced gravitational wave detectors. It is not unrealistic to think that the first gravitational wave signal of astrophysical origin will result from the joint detection of a short GRB in gamma-rays and GW (section 1.5.2). In this context it is very important to characterize short GRBs better, for instance by understanding their beaming pattern (which will tell us the fraction of binary mergers that produce GRBs) or looking for possible correlations between the properties of short GRB and the properties of their host galaxies. It is equally important to find practical ways to identify quickly GRBs originating from mergers in order to adapt the follow-up strategy for these sources.

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1.5 Some fascinating GRB related topics

The study of GRBs sheds light on several key questions of modern astrophysics, like the physics at work in astrophysical relativistic jets, the end of life of massive stars and the birth of stellar mass black holes, the history of massive star formation over the ages, the chemical enrichment of galaxies, etc. In the near future, it is expected that GRBs will contribute to the exploration of new domains, especially the young universe and multi-messenger astronomy. We quickly explain below how GRBs may contribute to these new fields.

1.5.1 Studying the epoch of reionization with GRBs

Several cosmological tools (the fluctuations of the cosmic microwave background, the baryonic acoustic oscillations, the spectra of distant quasars...) converge to show that the reionization of the universe ended around redshift 6. The history of reionization, however remains mostly uncharted, while it contains crucial information on the sources which reionized the universe. After the discovery of GRB 050904 at redshift z=6.3 and the measure of its optical spectrum [75], the interest for high redshift GRBs as probes of the intergalactic medium has been growing. Two recent examples are given by GRB 130606A at redshift z=5.91 [13, 14, 30, 76], and GRB 140515A at redshift z=6.33 [15]. The objective of measuring the optical spectrum of few GRBs at redshift beyond 7 is clearly within the reach of present instrumentation.

1.5.2 Short GRBs and gravity waves

The advent of the next generation of gravity wave (GW) interferometers, with an horizon of about 200 Mpc for the detection of mergers of binary neutron stars [42] raises serious hope for the detection of the first transient GW signals of cosmic origin. In this context the detection of a short GRB in coincidence with a GW signal is much awaited since it would simultaneously confirm our hypotheses on the nature of short GRBs and confirm the cosmic origin of the detected GW signal. One difficulty is that GRB monitors detect only a small fraction (few %) of mergers, those with the jet pointing towards the Earth. The majority of mergers within the reach of GW interferometers will not be associated with a signal at high energies. This has led several authors to study both theoretically and observationally the electromagnetic counterparts expected from a merger seen out of axis (see e.g. [50, 59]), these studies have evidenced the need for special observing strategies, but also the fact that with such strategies, it will be possible to confirm GW signals from nearby mergers ($z \leq 0.05$) with adequate follow-up at radio, optical and X-ray wavelengths.

1.5.3 Population III GRBs

With the detection of GRBs at redshift larger than 8, the question of the most distant GRBs in the universe has gained much attention in the recent years (e.g. [11, 48, 12, 17, 71, 74, 52, 85, 47, 67]). Despite the potential interest of these bursts, the detection of GRBs from the very first stars is challenging for the rarity of such events and for their properties (we expect these GRBs to be long and soft due to their high redshift). One additional difficulty may arise if low metallicity population III stars keep their external layers until the end of their life, leading to ultra long transients similar to ultra long GRBs detected in the local universe [25, 60]. The detection of more GRBs beyond redshift 8 in the coming years may clarify the appearance of very distant GRBs.

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2. SVOM, the next GRB mission

The aim of *SVOM* (**S**pace-based multiband astronomical **V**ariable **O**bjects **M**onitor) is to continue the exploration of the transient universe with a set of space-based multi-wavelength instruments, following the way opened by *Swift*. *SVOM* is a space mission developed jointly by China and France, under the responsibility of the space agencies of both countries and under the scientific responsibility of two principal investigators: Jianyan Wei from NAOC in China and Bertrand Cordier from CEA/IRFU in France. The mission features a medium size satellite, a set of space and ground instruments designed to detect, locate and follow-up GRBs of all kinds, a pointing strategy allowing the immediate follow-up of *SVOM* GRBs with ground based telescopes, and fast data transmission to the ground. The satellite carries two wide field high energy instruments: a coded-mask gamma-ray imager called ECLAIRs, and a gamma-ray spectrometer called GRM, and two narrow field telescopes that can measure the evolution of the afterglow after a slew of the satellite: an X-ray telescope called MXT and an optical telescope called VT. The ground segment includes additional instrumentation: a wide angle optical camera (GWAC) monitoring the field of view of ECLAIRs in real time during part of the orbit, and two 1-meter robotic follow-up telescopes (the GFTs). *SVOM* has some unique features: an energy threshold of ECLAIRs at 4 keV enabling the detection of faint soft GRBs (e.g. XRFs and high-z GRBs); a good match in sensitivity between the X-ray and optical space telescopes which permits the detection of most GRB afterglows with both telescopes; and a set of optical instruments on the ground dedicated to the mission. After a long period of indecision, the mission has recently been confirmed by the Chinese and French space agencies for a launch in 2021, and it has entered an active phase of construction this year (2014). We give below a brief description of the payload, the operations, and the scientific objectives of *SVOM*. More complete descriptions of the mission have been given by Paul et al.[55] and Godet et al.[26].

2.1 Space payload

2.1.1 ECLAIRs: the hard X-ray coded mask imaging camera

ECLAIRs is the instrument onboard the satellite that will detect and locate the GRBs. ECLAIRs is made of three parts: a pixelated detection plane (1024 cm^2) with its readout electronics, the coded mask and the shield defining a field of view of 2 steradians (89° x 89°), and a software that can detect and locate transient sources. The detection plane is made of 200 modules of 32 CdTe detectors each, for a total of 6400 detectors of size 4x4x1 mm. Each module is read by a custom ASIC connected to an electronics that encodes the position, the time and the energy of each photon. One of the requirement of ECLAIRs was to reach an energy threshold of few keV, in order to study soft GRBs like X-Ray Flashes and highly redshifted GRBs, the nominal energy range of the detection plane is 4-150 keV. The coded mask is a square of side 54 cm located at a distance of 46 cm from the detection plane, it has an opening fraction of 40% and provides a localization accuracy of several arcminutes ($\sim 14'$ for a source at the limit of detection). The instrument features a rate trigger and and image trigger, like *Swift*. These triggers are computed from the photon data, in several energy bands and on timescales ranging from 10 ms to several minutes. Our simulations show that ECLAIRs will detect 70-80 GRBs/yr.

2.1.2 GRM: the Gamma-Ray Monitor

GRM is a set of three detection modules, each made of a scintillating crystal (sodium iodide), a photomultiplier and its readout electronics. Each detector has a surface of 200 cm^2. The three modules have different orientations and they cover a total field of view of 2π steradians, providing a crude indication of the direction of detected GRBs. The energy range of the GRM is 15-5000 keV, extending the energy range of ECLAIRs towards high energies, to ensure the measure of Epeak for a large fraction of *SVOM* GRBs. We expect that GRM will detect > 90 GRBs/yr. GRM will have a good sensitivity to short hard GRBs, like the GBM of *Fermi*.

2.1.3 MXT: the Microchannel X-ray Telescope

MXT is a light X-ray telescope designed to measure the X-ray afterglow after a slew of the satellite. The telescope will use a novel technic to focus X-rays, based on micropore optics arranged in the lobster eye geometry. The use of micropore optics instead of full size mirrors permits a significant reduction of the size and weight of the telescope, fitting a medium size satellite like *SVOM*. The optics has a diameter of 21 cm and a focal length of 1 meter. MXT uses the radiation hard pn-CCD camera developed for the eROSITA mission [45, 62]. The camera of MXT has 256 x 256 pixels of size 75 μm. MXT has an energy range of 0.2-10 keV, an effective area of 50 cm^2, and a field of view of $64'$x$64'$. The localization accuracy of the MXT is $\sim 10''$ for 50% of the bursts, 10 minutes after the trigger. With a sensitivity of 7 10^{-13} erg cm^{-2} s^{-1} in 10^4 s, MXT will detect the afterglows of $\sim$ 90% of *SVOM* GRBs.

2.1.4 VT: the Visible Telescope

VT is a 40 cm Ritchey-Chretien telescope with a focal length of 3.6 m designed to measure the optical afterglows in the range 400-1000 nm, after a slew of the satellite. It has a field of view of $26'$x$26'$ and it is equipped with two 2k x 2k CCD cameras, one for the red channel (650-1000 nm) and one for the blue channel (400-650 nm). With a limiting magnitude R=22.5 in 300 s (dark sky), VT will detect the afterglows of at least 70% of *SVOM* GRBs.

2.2 Ground instruments and operations

The ground follow-up instruments constitute an important part of the mission. Three instruments are developed for the follow-up of *SVOM* GRBs: a wide angle camera that surveys a significant fraction of the sky for transients, and two robotic telescopes. In addition to these dedicated instruments, the *SVOM* collaboration will seek agreements with various existing telescopes or networks willing to contribute to the follow-up of *SVOM* GRBs.

2.2.1 GWAC: the Ground Wide Angle Camera

GWAC provides a unique way to survey a large field of view of 5000 sq. deg. for optical transients. The instrument will monitor 76% of ECLAIRs field of view, looking for optical transients occurring before, during and after GRBs. GWAC will also have its own trigger system, providing alerts to the world. GWAC is a complex system: the heart of the system is a set of 36 wide angle cameras with a diameter of 18 cm and a focal length of 22 cm. Together these cameras cover a field of view of 5000 sq. deg. They use 2k x 2k CCD detectors, sensitive in the range of wavelength 500-800 nm. These cameras reach a limiting magnitude V=16 (5 σ) in a typical 10 second exposure. This set of cameras is completed by a set of 12 "mini-GWAC" and two 60 cm robotic telescopes. The mini-GWAC cameras have a diameter of 7 cm, a focal length of 8.5 cm, and a field of view of 5000 sq. deg. They are sensitive in the range of wavelength 450-900 nm, and they reach a limiting magnitude V=13 (5 σ) in a typical 10 second exposure. The two 60 cm robotic telescopes are equipped with EMCCD cameras, they will provide multicolor photometry of the transients discovered by GWAC or mini-GWAC with a temporal resolution $\leq$ 1 sec.

2.2.2 GFTs: the Ground Follow-up Telescopes

The ground follow-up telescopes have two main goals. Firstly, they measure the photometric evolution of the optical afterglow in the first minutes after the trigger in a broad range of visible and NIR wavelengths, with a temporal resolution of few seconds. Secondly, when an afterglow is detected, they provide its position with arcsecond precision within five minutes of the trigger. Some essential features of the GFTs are their field of view, their size, and their sensitivity in the near infrared. The field of view ($\sim$ 30 arcminutes) enables observing quickly the entire error boxes of ECLAIRs. The size, typically 1 meter, allows the detection of all visible (i.e. non-dark) afterglows at the condition to arrive within few minutes of the trigger [1, 35]. Finally, the near infrared sensitivity permits the detection of high-z GRBs and GRBs extinct by dust, whose afterglow are obscured in the visible domain [27, 28]. GFTs are especially useful for the study of the early afterglow during the slew of the satellite, and for the rapid identification of the optical afterglow in various cases: when *SVOM* cannot slew to the burst or when the slew is delayed due to pointing constraints, and when the optical afterglow is only visible in the NIR.

2.2.3 Operations

In order to facilitate measuring the redshifts of GRBs detected with ECLAIRs, the instruments of *SVOM* will be pointed close to the anti-solar direction. This ensures that *SVOM* GRBs will be in the night hemisphere and quickly observable from the ground. As soon as a GRB will be located, its coordinates and its main characteristics will be sent to the ground within seconds with a VHF antenna. The VHF signal will be received by one of the $\sim$ 40 ground stations distributed around the Earth below the orbit. The data will then be relayed to the Operation Center, which will send *SVOM* alerts to the internet via the GCN and VOEvent networks (http://gcn.gsfc.nasa.gov/), and to the ground instruments GWAC and the GFTs. *SVOM* can also perform target of opportunity observations (with MXT and VT for instance), with a delay of few hours, which depends on the availability of uplink communication with the satellite.

2.3 Scientific objectives

The main science goal of *SVOM* is the study of cosmic transients detected in hard X-rays and in the optical. While, the mission has been designed for the study of GRBs it is also well suited for the study of other types of high-energy transients like tidal disruption events, active galactic nuclei, or galactic X-ray binaries and magnetars. For this type of sources, *SVOM* is both a "discovery machine", with wide-field instruments that survey a significant fraction of the sky

(ECLAIRs, GRM and GWAC), and a "follow-up machine", with fast pointing telescopes in space and on the ground (MXT, VT, and GFTs) that provide a multi-wavelength follow-up of remarkable sources, with good sensitivity and a high duty cycle. The follow-up can be triggered by the satellite itself or from the ground, upon reception of a request for target of opportunity observations (ToO).

We discuss below some objectives of *SVOM* for GRBs, as they are described in the Science Requirement Document of the mission.

2.3.1 GRB with redshifts

One essential goal of *SVOM* is to get GRBs with a redshift. The redshift is required to measure the energetics of the burst and the epoch at which the GRB occurred in the history of the universe. Four elements in the design of the mission concur to facilitate the measure of the redshift for *SVOM* GRBs: a near anti-solar pointing ensuring that *SVOM* GRBs can be quickly observed with ground based telescopes, a good sensitivity of the on-board optical telescope permitting the rapid identification of high-z candidates (which are not detected at visible wavelengths), NIR follow-up on the ground to look for the afterglows of dark GRBs, and agreements with the community to promote the optical spectroscopy of *SVOM* GRBs with large telescopes. With this strategy we expect to measure the redshift of more than 50% of *SVOM* GRBs, constructing a sample that is more representative of the actual GRB population than the *Swift* sample.

2.3.2 GRB progenitors

In order to get a better understanding of the GRB phenomenon *SVOM* is designed to detect all kinds of GRBs, and to provide extensive multi-wavelength observations of the prompt GRB and its afterglow.

The ability to detect *soft GRBs* with a spectral energy distribution (SED) peaking below 20-30 keV will favor the detection of X-ray flashes [31, 34, 5, 64, 65, 56]. These faint GRBs can only be detected if they are close enough and if their spectral energy distribution peaks at low energies (because faint GRBs with a SED peaking at high energies radiate too few photons to be detected). The detection of X-Ray Flashes in the local universe ($z\leq 0.1$) will permit detailed studies of their associated supernovae (as was the case for XRF 020903 [68]), providing crucial clues to understand the broader context of the SN-GRB connection.

SVOM will also contribute to clarify the origin of *short GRBs*, especially with the possibility to search for GRBs in coincidence with the signals detected by advanced gravitational waves (GW) detectors. The favorite scenario for the production of short GRBs is the coalescence of two compact objects (two neutron stars or a neutron star plus a black hole), which predicts that short GRBs are accompanied by powerful bursts of gravitational waves. One complication of these searches is that GRBs are much more beamed than gravitational waves. Considering that we detect 1 short GRB out of $\sim$50 mergers [51, 9], and a moderate enhancement of the gravitational wave emission along the jet, we expect that about 10% of the mergers detected by advanced detectors of gravitational waves will be associated with a GRB. Assuming a rate of binary mergers of 50/yr within the horizon of GW detectors ($\sim$400 Mpc), we expect to detect $\sim$3 events coincident with GW triggers with ECLAIRs, and $\sim$9 with GRM, in 5 years of operation. *SVOM* will also have the capability to point its narrow field instruments towards candidate sources of GWs. We evaluate that 15 events

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approximately can be followed quickly (6 hours) with *SVOM* narrow-field instruments in 5 years of operation.

2.3.3 GRB physics

The instrument suite of *SVOM* will provide good multi-wavelength coverage of GRBs. For those occurring in the field of view of GWAC, the prompt emission will be measured from 1eV to 5 MeV, with GWAC, ECLAIRs, and GRM, and the prompt optical emission may also be observed by one GFT for GRBs lasting longer than 40 seconds. GRB afterglows will be observed with the two narrow-field instruments on-board the satellite and with the ground follow-up telescopes on Earth. For some GRBs, *SVOM* will provide a very complete view of the phenomenon and its evolution, hopefully bringing new insight into the complex physics at work in these events. A lesson of *Swift* is that a few well observed GRBs may crucially improve our understanding of GRB physics, as was the case for GRB 130427, a bright nearby burst detected by *Swift*, *Fermi* and various optical and radio telescopes on the ground [2, 3, 4, 8, 19, 21, 37, 39, 40, 43, 44, 46, 54, 57, 63, 72, 77, 81, 82, 84].

The physical processes at work within the jet remain mysterious even after the observation of hundreds of GRBs. Comprehensive discussions of the theoretical challenges connected with the understanding of the prompt GRB emission can be found in Zhang [88], and Zhang and Kumar [38]. These authors show that several crucial questions connected to the physics of the ultra-relativistic jet and its interaction with the surrounding medium remain unanswered, like the nature and content of the jet (is the energy stored in the baryons of in magnetic fields?), the mechanisms of its acceleration, the microphysics and the dominant radiation processes, the importance of the reverse shock, the role of pairs, etc. Performing multi-wavelength observations during the prompt emission and the early afterglow, *SVOM* will provide key observations to understand the physics of relativistic jets. GRBs detected with *SVOM* will also benefit from contemporaneous or follow-up observations with a novel generation of powerful instruments, like CTA (the Cerenkov Telescope Array) for very high energy photons, LSST (Large Synoptic Survey Telescope) for optical transients associated with on-axis and off-axis GRBs, the precursors of SKA (the Square Kilometer Array) in radio, and JWST (James Webb Space Telescope) for the study of the hosts of very distant GRBs.

2.3.4 Cosmology

GRBs are like "fireworks" in the distant universe. Their extreme luminosity permits their detection in hard X-rays up to very high redshifts (z> 10) and the spectroscopy of the optical afterglow provides the redshift of the burst and a tomographic vision of the line of sight to the burst. With *Swift* and the measure of about 300 redshifts, GRBs are providing new diagnostics of the distant universe. When the signal to noise ratio (SNR) of the optical spectrum of the afterglow is sufficient, we get detailed information on the circumburst medium, on the gas and dust in the host galaxy, on the intergalactic medium and the intervening systems. With a smaller SNR, the measure of the redshift allows locating the time of the explosion in the history of the universe and reconstructing the history of the GRB formation rate, which reflects the formation rate of massive stars.

There is of course a special interest in very distant GRBs ($z > 5$), which provide a unique view on the young universe, especially since they occur in galaxies which are undetectable with other methods of observation. One exciting challenge of GRB missions is the detection of GRBs resulting from the explosion of population III stars (the first generation of stars formed with pristine gas containing no metals). Such events are expected to be rare, to occur at high redshifts, to have no detectable hosts (except in absorption in the spectrum of their optical afterglow) and afterglows that are only detectable in the near infrared. They could be similar to some very long GRBs found at lower redshift [48, 52, 25, 18, 41, 60]. We expect to detect about 5 GRBs/yr at redshift $z > 5$ with ECLAIRs, but they will be useful only if we can measure their redshift. One difficulty is that the optical afterglows of GRBs fade very quickly, and after a few hours they are often too faint to permit measuring the redshift of the burst. In order to quickly identify high-z candidates that deserve deep spectroscopy in the NIR, we rely on the sensitivity of VT and on fast NIR follow-up telescopes on the ground. Dark GRBs, whose afterglows are not detected in the VT, are good candidates for high-z bursts, but they can also be extinct by dust in the vicinity of the source. The nature of these events (distant of extinct GRB) will be confirmed quickly with fast visible/NIR photometry from the ground, allowing the most appropriate spectroscopic follow-up.

3. Conclusion

Gamma-Ray Bursts are remarkable cosmic phenomena, raising outstanding theoretical and observational challenges, and at the same time giving us new tools to explore the physics of relativistic jets, the death of stars, the birth of black holes, the distant universe, and the buildup of cosmic structures over time. Thanks to the remarkable success and longevity of Swift, to efficient ground follow-up efforts, and theoretical advances, our understanding of GRBs has made huge progress in the past years. The future appears also bright with new instruments in preparation, like the advanced gravity wave detectors, kilometric scale neutrino detectors, extremely large ground telescopes and new GRB satellites like SVOM. There is no doubt that GRB studies will remain at the forefront of astrophysics in the coming years.

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DISCUSSION

SERGIO COLAFRANCESCO: Is there any plan for *SVOM* to observe/monitor Terrestrial Gamma-ray Flashes (TGFs)?

JEAN-LUC ATTEIA Yes, the gamma-ray instruments of SVOM will remain active when SVOM will look at the Earth, offering the possibility to detect TGFs.

SIMON VOJTECH: Are there any observable indications that short GRBs have wider jets than long GRBs, for example from the light-curves of their afterglows?

JEAN-LUC ATTEIA Edo Berger, in his review of short GRB properties [9] mentions a beaming factor ~ 70 for short GRBs about two times less than for long GRBs.

SOLEN BALMAN: What is the probability density of GRBs of various types, for instance within a volume 1Mpc? May you get a GRB in a million year within this volume?

JEAN-LUC ATTEIA The rate of long GRBs is 100-1000 GRBs/Gpc^3/yr, or 1 GRB per million year per Mpc^3. The rate of supernovae of type Ibc is about 9000/Gpc^3/yr, about 10 per million year per Mpc^3, the rate of long GRBs cannot exceed this rate.

WOLFGANG KUNDT: Why have we never been able to see a GRB jet illuminating some nearby domain of our own Galaxy?

JEAN-LUC ATTEIA The closest GRB found until now is GRB 980425 located at 36 Mpc, this is much too far to see detectable effects in our Galaxy. On the other hand, we expect one GRB to occur within our Galaxy every ~ 10 million years, thus leaving no trace in the Galaxy.