Prospectives IN2P3 - GT04 astroparticules

The Science of SVOM at IN2P3

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1 Introduction

To take advantage of the astrophysical potential of the study of the transient sky with a special focus on extreme explosive events such as Gamma-Ray Bursts (GRBs), Chinese and French astrophysicists have engaged in the SVOM mission (Space-based multi-band astronomical Variable Objects Monitor).

The SVOM mission will be one of the key projects devoted to the study of the transient sky in the 2022-2027 period. The mission has been approved in 2014 and IN2P3 has contributed since this starting point. Today, 4 IN2P3 laboratories are strongly involved in the mission project and its scientific preparation: APC, CPPM, LAL and LUPM. INSU is involved through the implication of 5 laboratories and CEA with different IRFU laboratories.

The implication of IN2P3 laboratories in the SVOM mission comes as an extension of their respective primary scientific topics of interest, e.g., ultra-high energy cosmic rays for APC, neutrinos for CPPM, gravitational waves for LAL, and GRB high-energy astrophysics for LUPM. The SVOM mission, with the diversity of the science goals addressed by its Core Program (GRBs), ToO Program and General Program, is a bridge that links all those fundamental scientific themes, well within the perimeter of the IN2P3 astroparticle research field and strongly connected to several IN2P3 experimental projects (CTA, Virgo, KM3NeT, LSST, etc).

2 Context

The SVOM satellite will be launched in December 2021. It will be inserted into a Low Earth Orbit with an inclination of 30°, at an altitude of 625 km with an orbital period of ~96 min. The SVOM payload will carry two wide field of view (FoV) high-energy instruments: a coded-mask gamma-ray imager (ECLAIRs) and a gamma-ray spectrometer (GRM). They will be accompanied by two narrow field telescopes: a Microchannel X-ray Telescope (MXT) and a Visible-band Telescope (VT). The SVOM ground segment includes additional instruments: a wide angle optical camera (GWAC) monitoring a part of the ECLAIRs FoV in real-time, and two 1-m-class robotic follow-up telescopes (the GFTs).

At the beginning of the next decade, SVOM will be the main provider of GRB alerts, positions and temporal/spectral parameters on very short time scales. The SVOM instrumentation composes a unique multi-wavelength observatory with rapid slew capability that will find multiple applications for the whole astronomy community beyond the specific objectives linked to GRBs (see contribution “X-ray astroparticle” by A. Goldwurm). For example, the SVOM mission has been conceived to promptly scrutinize the celestial fields where sources have been detected by wide field-of-view astronomical devices such as the upgraded generation of gravitational wave detectors (advanced Virgo/LIGO) and high-energy neutrino detectors (KM3NeT, IceCube).

The astronomical panorama of the next decade will be shaped by new instruments developed to address various outstanding questions raised by present-day astrophysics. This panorama encompasses large radio, infrared, visible and gamma-ray telescopes, advanced gravitational wave interferometers and km^3-large neutrino detectors, as well as simulations with powerful computers. Young fields, like Time Domain Astronomy and Multi-Messenger Astrophysics are also expected to grow very fast, bringing new discoveries (it already started splendidly with GW170817). At the French national level, the PNHE program and the "Transient Sky 2020" network will help foster collaborative projects across scientific consortia (see contribution “Le ciel transitoire et le réseau TS2020” de F. Piron).

3 SVOM advances on GRB science

SVOM is designed to study the physics of the GRB phenomenon in all its diversity, thanks to an excellent spectral and temporal coverage of the prompt and afterglow emission, combined with an optimized follow-up strategy aiming at the redshift determination for a large fraction of GRBs (~ 2/3). GRBs are divided into two main classes. Long GRBs (LGRBs, with a typical prompt emission duration >2s) are generally associated with the collapse of some massive stars (collapsar model) and the emission of a relativistic ejecta. Short GRBs (SGRBs) are thought to be due to the collision of a neutron star and a black hole or a pair of neutron stars in a binary system due to orbital decay caused by the emission of gravitational radiation (and confirmed in the case of GRB170817A associated with the GW170817 event). Additionally Ultra-long GRBs (with typical durations >1000s) are possibly originating from a third class of progenitors, and are well suited to be detected by SVOM thanks to its long-duration pointing strategy.

3.1 Physical origin of GRB emission

The nature of the physical mechanism that launches GRB ultra-relativistic jets is not elucidated, and the composition of the jet (energy reservoir, electromagnetic or matter dominated) is currently the subject of an intense debate, as well as the internal dissipation mechanism responsible for the prompt emission (photospheric emission vs internal shocks vs magnetic reconnection). The microphysics in the emission regions remains unclear, especially the acceleration of the electrons responsible for the non-thermal emission and the identification of the associated radiative processes (synchrotron emission, inverse Compton scattering, etc.). Following past and recent GRB studies conducted at IN2P3 in the context of the Fermi mission, progress in this field will require to observationally constrain the physical conditions in the jet when the prompt emission is produced: radius, Lorentz factor, magnetization, magnetic field geometry, etc.

Regarding the interaction of the ejecta with the circumburst medium and the physical origin of the afterglow, several emission regions are invoked: shocked external medium (forward shock), shocked ejecta (reverse shock), late internal shocks, etc. Some of these models have strong implications on the lifetime and energetics of the central engine as they imply late energy injection by the source or relativistic ejection at late times. A good description of both the prompt and afterglow emissions simultaneously is also necessary to test models linking some afterglow features with the prompt emission. Discoveries of LGRB orphan afterglows, that are expected from LSST, as well as gravitational wave detections of SGRBs, will bring additional constraints on the system (jet opening and viewing angles, jet structure, shocks with the surrounding material) and rest-frame energetics.

3.2 Short GRBs and the compact star merger model

In the widely-accepted scenario, SGRBs have a formation mechanism independent of that of the LGRBs. SGRBs occur at a significant distance from their host galaxy, as expected if their progenitors are the very long-lived NS-NS or NS-BH systems which have received a significant kick at the time of their creation. Like for LGRBs, a highly relativistic jet along the rotation axis is pointed in our direction, producing the observed gamma-ray burst. The compact star merger model of SGRBs leads directly to two predictions (and confirmed in the case of GW170817): the simultaneous production of strong gravitational wave emission from the final stages of orbital decay and merger, and the substantial production of r-process elements in the neutron-rich merger ejecta. The complementarity of the SVOM instruments will allow us to get redshift measurement in a large fraction of event but also a complete coverage of the visible light emission through the GWAC, GFTs and VT (also catching the kilonova emission if existing). The combination of ECLAIRs and GRM will allow for a better understanding of the prompt emission and the MXT instrument will permit a precise localization and measurement of the early phase of the afterglow emission.

3.3 GRBs as particle accelerators

Electrons and hadrons are accelerated on a very short timescale at the shock fronts in the jets to ultra-relativistic speeds. In the standard framework, the gamma-ray emission is generally explained by the emission of relativistic electrons. However, hadronic models have been invoked in several cases to explain the gamma-ray emission measured by the Fermi/LAT at GeV energies. The recent detections of VHE emission from 3 GRBs up to a few hundreds of GeV by MAGIC and H.E.S.S. have also proven the acceleration of particles up to these very high energies. These detections are clearly very encouraging for CTA which should detect multiple GRBs with a relatively high statistics. One of the next challenges will be to push the limit on the maximum photon energy with CTA, HAWC and LHAASO in the Northern hemisphere and the project SWGO in the Southern hemisphere.

GRBs have been proposed as one of the potential sources for ultra-high energy cosmic rays (UHECRs) with energy up to 10^{20} eV. The detection of a high-energy neutrino (HEN) signal in coincidence with a GRB would be a direct proof of the existence of a hadronic component in the jets. The ANTARES and the IceCube detectors are currently the most sensitive neutrino telescopes in operation in the Northern and Southern hemispheres, respectively. So far, no neutrino signal has been detected in coincidence with a GRB, leading to a very stringent limit (<10%) on the fraction of standard GRBs that contribute to the high-energy neutrino diffuse flux (using standard hadronic modelisation). The contribution of a dominant population of low-luminosity and/or choked GRBs, largely missed by current gamma-ray satellites, may still be a major source of HEN. During the SVOM operations, the KM3NeT detector in the Mediterranean Sea will achieve an instantaneous sensitivity comparable to the current IceCube telescope (see contribution “Multi-messenger neutrino analysis” by D. Dornic). After 2025, the IceCube Collaboration also plans to extend its array to 10 km^3. SVOM will be more efficient in the detection of such GRB populations thanks to the ECLAIRs low-energy threshold of 4 keV, therefore providing a new sample to search for correlated neutrino emission. Thanks to the performance of its instruments, to their large multi-wavelength coverage, and to the excellent space-ground synergy, SVOM will provide a sample of well characterized GRBs, which is primordial for the search of their potential HEN counterparts. Joint analyses between CTA and KM3NeT of SVOM GRBs will provide insights on their capability to be efficient cosmic accelerators.

3.4 Cosmology and Fundamental Physics

The determination of GRB jet opening angle and redshift is also fundamental to test the correlations found between some quantities related to the gamma-ray prompt emission of LGRBs. These correlations can in principle be used to extend the Hubble diagram to high redshift and to determine cosmological parameters, but their physical explanations are still unknown and there is still an open debate on their robustness.

The search for New Physics with GRBs can be performed by analysing the times of arrival of high energy photons emitted during GRB prompt emission, in order to set stringent constraints on Lorentz Invariance Violation (LIV). Such studies were conducted in the past in IN2P3 laboratories using Fermi/LAT data, thoroughly investigating statistical methodologies and systematics uncertainties. These efforts led to the first Planck-scale lower limits on deterministic and stochastic LIV. In the future, setting even tighter limits on the Quantum Gravity energy scale will be possible using GRBs jointly detected by SVOM and CTA.

4 Multi-Wavelength and Multi-Messenger Astronomy with SVOM

4.1 Synergies with present large electromagnetic observatories

SVOM has multiple roles to play as it can: (1) follow-up triggers from other facilities, including multi-messenger facilities, and any candidate counterparts found by other electromagnetic facilities; (2) trigger multi-wavelength follow-up of SVOM triggers, including faint sources found in ground analysis which did not result in an on-board trigger and sources found with the ground-based SVOM facilities; (3) monitor sources likely to undergo a transient phase; and (4) survey classes of transients to provide population information. These types of observation will require detailed planning to avoid overwhelming the observational limits of SVOM given the sheer number of triggers that will emerge from the wide-field transient machines. The latter issue is perhaps the greatest challenge facing astronomy – how to decide what to observe?

In terms of likely (known) classes of sources there are several of particular importance for us, like GRBs detected from other facilities (e.g. Fermi) and for which we can trigger dedicated SVOM follow-up. LSST and other optical facilities will find very large numbers of supernovae, including rare classes demanding prompt follow-up. LSST will also be able to detect orphan GRBs or orphan kilonovae, triggering follow-up searches for X-ray counterparts with MXT, possibly on long time scales (weeks) in the latter case. Early collaboration and coordination with brokers refining the large LSST streams of alerts such as the IN2P3 initiative, Fink, is a guarantee for efficient communication and operations between observatories (see contribution "Listening to the transient sky in the LSST era"). SVOM can observe in the optical and X-ray domain to look for information about the environment and progenitor. CTA will probe the very high energy sky in much greater depth and over larger areas than currently achievable, similar to SKA in the radio and LSST in the optical domain. The MXT instrument on board SVOM will also be a valuable alternative to Swift-XRT to study flares from blazars and other active galactic nuclei. X-ray observations of TeV blazars, which will be observed with exquisite sensitivity by CTA, provide a direct probe into the population of particles responsible for both emissions (see contribution "Extragalactic γ-ray Astrophysics" by D. Horan).

4.2 Follow-up of GW candidates

Multi-messenger astronomy has been discussed for a long time for its ability to shed light on the physical processes giving birth to GRBs in the case of gravitational waves or on the acceleration mechanisms in the jets for neutrinos and gamma-rays (see contribution “Multi-messenger astroparticle physics” by N. Leroy). In the very first moments following the explosion, the photons do not escape the dense medium and one must rely on new messengers to bring some information. The detectors for those messengers are becoming mature. Gravitational waves have finally been discovered and astrophysical neutrinos have been observed. In this new multi-messenger astronomy era, SVOM with its ground and space instruments will offer a large and complementary follow-up capability through ToOs (Target of Opportunity). GWAC with its 5000 sq. deg. coverage can start the observation since the alert reception. The GFTs with their small field of view will confirm GWAC candidates and will be able to do follow-up for well localized events. To activate the satellite instruments, we will rely on a specific ToO program to send the observation program using S-band stations. This program guarantees less than 12 hours between the alert and the start of space observations (less can be expected for most cases) and can be activated about once per week. From space, MXT and its 1 sq. deg. field of view will have the possibility to cover larger sky portion using a specific tiling procedure.

4.3 Follow-up of astrophysical neutrinos

A HEN diffuse flux of cosmic origin has been identified by the IceCube telescope in 2012 and confirmed later with all neutrino flavours. One of the major results is undoubtedly the detection of a high-energy neutrino detected by IceCube on September 22, 2017, likely associated with a flare of the blazar TXS 0506+056 seen by gamma-ray, X-ray, optical, infrared, and radio telescopes. If confirmed in the future, this association may mark the real birth of the high-energy neutrino astronomy. ANTARES is also detecting a mild excess of neutrino events in both track and cascade channels at very high energy. However, the event statistics is too low to claim a discovery. With the new generation of neutrino telescopes, we can expect a larger statistics with IceCube Gen2 and an angular precision lower than 0.1(1.5)º for $\nu_\mu(\nu_{e,\tau})$ neutrinos with KM3NeT. The main requirement for multi-messenger studies is the quasi-online communication of potentially interesting observations to partner instruments (“alerts”), with latencies of a few minutes, at most. Such alerts are the only way to achieve simultaneous observations of transient phenomena by pointing instruments. IceCube and ANTARES have set an alert program more than 10 years ago. For the next generation, these alert programs will be one of the prime source finding programs (see contribution "Multi-messenger neutrino analysis" by D. Dornic). Ultra-high energy earth-skimming neutrinos can be detected by the large cosmic-ray arrays (Pierre Auger Observatory and GRAND, see contribution “Towards uncovering the origin of ultra-high energy cosmic rays at the Pierre Auger Observatory” by O. Deligny) and by several radio projects (ANITA, ARA, ARIANNA, RNO).

SVOM with its ground- and space-based instruments will offer large and complementary follow-up capability through ToOs. The performances of SVOM (fields of view and instrument sensitivities) are perfectly tailored to follow all neutrino alerts with the MXT and VT instruments on-board and ground-based telescopes (GFTs and GWAC).

Reference

Wei, J., Cordier, B. et al. (SVOM consortium), “The Deep and Transient Universe : New Challenges and Opportunities - Scientific prospects of the SVOM mission” (SVOM white paper, https://arxiv.org/abs/1610.06892) and references therein