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

Foreword

Discovery

Gamma-ray bursts (GRBs) were discovered in 1967 by the *Vela* US military satellites monitoring the Earth for the gamma-ray radiation emitted when nuclear bombs are detonated. What they unexpectedly saw were random bursts of gamma-ray radiation of astrophysical origin, appearing at a rate of about one a day. The intense radiation is extremely brief, lasting for a few milliseconds to a few hundreds seconds before disappearing. Up to recently, gamma-ray detectors designed to monitor vast sections of the sky had always poor positional accuracy ($\sim$ degree). The lack of a good source position and the short duration of the phenomena stalled the search for counterparts at other wavelengths for nearly 30 years, delaying the measure of their distance and energetics. The story of their discovery, almost straight out of a cold war spy novel, and their elusive nature captured the imagination of astrophysicists like few other objects have. Astrophysical lore has it that at some point there were more theories on GRBs than observed GRBs. The mystery was all the more tantalizing that gamma-ray bursts are neither rare nor extremely difficult to detect at high energies and that a steady stream of observations has continuously added new bursts to the puzzle.

Cosmological distances

When the mystery of their distance was finally solved in the 1990s, the interest for GRBs became even greater, as the most extreme assumption was revealed to be true. This occurred with two major steps. First, the instrument BATSE onboard the *Compton Gamma-Ray Observatory* observed hundreds of GRBs and conclusively showed that their spatial distribution was isotropic, ruling out the dominant class of models which had GRBs originating in our Galaxy (this would have shown up as an overdensity in the Galactic Plane). The BATSE catalog of more than 2500 bursts includes well measured temporal and spectral properties, which revealed the existence of two classes of GRBs, short ($\sim$ a few tens to hundreds of milliseconds) and long ($\sim$ a few seconds to hundreds of seconds). Second, the Dutch–Italian *BeppoSAX* satellite was able to identify in 1997 a counterpart in X-rays, enabling GRB positions to be determined for the first time with arcminute accuracy within a few hours. Superb organization was then required to ensure a quick turnaround between the detection of the GRB and the observation of its counterpart with ground-based telescopes. Several groups were able to point telescopes quickly enough towards the new accurate positions where they caught fading GRB optical and radio *afterglows*. Spectroscopy in the optical range is a powerful tool for the astronomer. It revealed that the afterglow spectrum was highly redshifted, a well known signature of the most distance sources which is due to the expansion of the Universe. This proved once and for all that GRBs occur at cosmological distances ($\sim$ billions of lightyears), in faraway galaxies, whose faint emission is detected in many cases once the afterglow has faded.

Relativistic outflows

The discovery of afterglows closed a long controversy and started a new chapter in research on GRBs. Cosmological distances imply that GRBs are the most energetic explosive phenomena known in the Universe. The energy released as radiation in a GRB can reach a few 10^{54} erg (assuming isotropic emission): the equivalent of the mass of our Sun converted to pure energy. The gamma-ray prompt emission is highly variable, down to timescales of milliseconds. The size of the emitting region must therefore be very small. The concentration of so much energy in so small a volume inevitably leads to the production of e^+e^- pairs by photon–photon annihilation, which should prevent any significant gamma-ray emission. However, this contradiction is lifted if the emission occurs in a medium moving at relativistic speeds towards the observer since the proper times and lengths then appear contracted. GRBs are therefore thought to be associated with highly relativistic outflows that happen to be moving along our line-of-sight. The bulk motion should typically have a Lorentz factor of 100 or larger, which corresponds to a velocity within 0.005% of the speed of light! The observation of superluminal motion in radio afterglows has confirmed this basic picture.

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Gamma-ray bursts and massive stars

Observations during the past decade have established a link between GRBs and massive stars. Some long GRBs have been associated to supernovae, the best case being GRB 030329 detected by the American–French–Japanese HETE2 satellite and firmly associated to a supernova of type Ic, i.e. the explosion of a very massive star. Therefore GRBs probably signal the collapse of a massive star and the following formation of a compact object, most probably a rotating black hole. Statistics indicate however that only a small fraction of such gravitational collapses lead to GRBs: why and how some massive stars give rise to GRBs remains a fundamental question to answer. The properties of short GRBs and their host galaxies point to an other origin. The merger of a compact binary (two neutron stars or a neutron star and a black hole) is favored. It leads also to the formation of a black hole surrounded by a thick accretion disk. In both scenarios the gravitational energy released in a collapse or merger is sufficient to explain GRBs if part of it is channeled into a collimated, relativistic jet. Such relativistic ejections by an accreting black hole are commonly observed in many other astrophysical sources. Corrected for relativistic beaming, the radiated energy in GRBs seems to be reduced to about 10^{51} erg. Fast variability indicates that the prompt emission is produced within the relativistic jet, possibly from mildly relativistic shocks occurring when fast-moving ejecta catches up with slower-moving material ejected earlier. The afterglow emission is the signature of the deceleration of the jet by the ambient medium, that leads to a strong relativistic external shock propagating forwards and a reverse shock that crosses the ejecta. However, many of the physical processes remain sketchy, even more so as observations have continued to bring in surprises. For instance, the *Swift* satellite which has increased significantly the rate of accurate localizations and allowed for the first time to observe without any gap the transition from the prompt emission to the afterglow, has revealed a completely unexpected evolution in the first minutes to hours following the burst, including in many cases a flaring activity. Deep follow-up observations with large telescopes or very fast observations with automated telescopes triggered by satellites now show a diversity of behavior in GRBs that challenges the coda inherited from the *BeppoSAX* days.

Gamma-ray bursts as a tool

The past decade has also seen GRBs studies expand well beyond their initial subfield of high energy astrophysics. Studies of relativistic jet physics in GRBs connect naturally to studies of jets in X-ray binaries or active galactic nuclei. GRBs have also become a staple of astroparticle physics because of their potential as sources of ultra-high energy cosmic rays, particles of cosmic origin with energies greater than 10^{20} eV that have been observed by detectors on Earth, and high energy neutrinos. Particle acceleration and emission at relativistic shocks in GRBs stretches plasma physics to its limits. GRBs have also rejuvenated the study of core-collapse supernovae. Merging compact objects offer the promise of detecting gravitational waves concurrent with a GRB. Finally, GRBs have begun to be used as probes of the high redshift, early Universe. One of the most distant known object is GRB 090423 at a redshift of 8.2 (GRBs are numbered by their date, hence this one was discovered on April 23, 2009). The Universe was only 600 millions years old when this event took place. This detection already proves that massive stars had time to form, live and die in this early Universe and illustrates the great potential of GRBs for cosmology. The French–Chinese mission *SVOM* builds upon those promises and is set to search for the highest redshift GRBs after its launch in the second half of this decade.

GRB studies in the SVOM era

This issue of the *Comptes Rendus de l'Académie des Sciences* is intended to give a report, accessible to a non-specialist audience of physicists, on the present state of GRB research and on its perspectives in the coming years. Bing Zhang provided a complete panorama of GRB physics and the challenges theorists currently face at the end of 2010. The multi-wavelength context in 2015, as *SVOM* prepares for launch, is described by Joachim Greiner and Arne Rau. Particle acceleration is of fundamental interest to link observations with physical conditions in the source. Guy Pelletier and Martin Lemoine describe the current status of the theory and the hurdles it faces. Numerical simulations have become an invaluable tool to understand the central engine of GRBs and the connection to supernovae. Jérôme Novak summarizes efforts in this direction and the prospects for detection of gravitational waves from GRBs. Fast follow-up of GRB alerts is the key for all studies. Jean-Luc Atteia and Michel Boër present the results from prompt emission of GRBs and the state-of-the-art in trigger response. The *Fermi Gamma-Ray Space Telescope* has recently opened up a window into GRB emission above 100 MeV. Frédéric Piron and Valerie Connaughton explain how this completes our view of GRB prompt emission. The *Swift* observations of afterglows have led to major revisions in the standard picture of how GRBs develop. Robert Mochkovitch and Olivier Godet detail the impact from both observational and theoretical point-of-views. GRBs have generated lots of interest as probes of the distant Universe. Patrick Petitjean sets out the prospects and limitations to expect. SVOM will have a broader energy coverage compared to the preceding missions. It is expected to become the main provider of GRB alerts to the community after its launch in the second part of this decade. Jacques Paul, Jianyan Wei, Stéphane Basa and Shuang-Nan Zhang describe its scientific goals and planned performance.

The contributors have all provided high quality reviews that can be used as a wide-ranging, up-to-date yet accessible introduction to GRBs for graduate students and interested scientists. We thank them for this effort as GRB research continues to progress astonishingly fast. An up to date bibliography can be found in each contribution. In addition, the interested reader may also wish to consult the more specialized reviews listed below [1–4]. We believe that this issue testifies to the vitality of the ongoing research effort and it is our hope that, perhaps, it will convince new scientists to join in the excitement of studying some of the most astounding objects in the Universe.

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