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GRBs as multimessenger sources

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Summary. — Gamma-Ray Bursts are center stage in the new era of multi-messenger astronomy, as their nature is probed through photons, gravitational waves (GW), neutrinos and cosmic rays. Discovered thanks to their powerful multi-wavelength electromagnetic signal, they have been linked to the explosion of very massive stars ("long GRBs"), or to the coalescence of compact objects ("short GRBs") which also produce a GW signal. GRBs are also believed to be efficient particle accelerators, as required by the observation of high-energy photons up to $\sim 100\,\mathrm{GeV}$. Therefore, quite naturally, they have been proposed as possible sources of the mysterious ultra-high-energy cosmic rays (UHECRs), with energies above $10^{18}\,\mathrm{eV}$. However, some of the current models that simultaneously produce high electromagnetic fluxes and high-energy cosmic rays necessarily produce neutrinos as well, with a flux which appears to violate the limits recently set by the IceCube detector. I will review the observational features of GRBs as multi-messenger sources, as well as their link to theoretical models.

1. – Introduction

Gamma-Ray Bursts are ultra-relativistic systems emitting bursts of hard X-rays and γ-rays lasting between a fraction of a second to a few minutes (*prompt* emission) followed by a long-lasting decaying emission at all wavelengths (*afterglow* emission). Their energy output is very large, between 10^{50} and 10^{52} erg when accounting for beaming [1]. It is widely believed that the electromagnetic emission is originated within a relativistic jet, produced by the collapse of a large star ("long GRBs", with duration $> 2\,\mathrm{s}$) or the merger of a Neutron Star (NS) and a black hole (BH) or two NSs ("short GRBs", with duration $< 2\,\mathrm{s}$). There are two different families of models currently used in the interpretation of the prompt emission. In the first family (the so-called *standard fireball model*) the highly-variable prompt emission is attributed to synchrotron emission from particles accelerated in multiple internal shocks, *i.e.*, shocks that occur when a faster shell ejected by the central engine collides with a slower shell within the outflow. Such a scenario has been used to explain the non-thermal spectrum that characterizes GRBs. The efficiency that internal shocks can achieve in converting energy into radiation appears to be insufficient to explain the luminosity of some GRBs [3, 4] unless the spread in the Lorentz factor between the colliding shells is large [5]. Also, a non-negligible fraction of

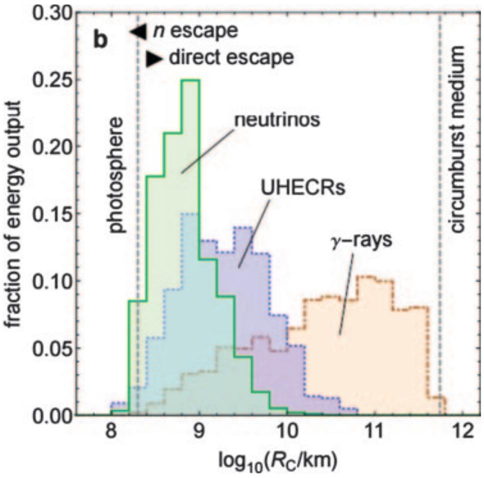

Fig. 1. – Fraction of total energy output in different messengers as a function of the internal shock radius R_c (reproduced by permission from Macmillan Publishers Ltd: Bustamante *et al.*, Nature Communications, **6** (2015) 6783, copyright (2015) [2], `http://dx.doi.org/10.1038/ncomms7783`).

GRBs show spectra that are difficult to explain with pure synchrotron emission [6-8]. For this reason, some GRBs have been modeled with phenomenological models adding a thermal component to the non-thermal one [9-14].

Because of these issues with the so-called "standard" fireball paradigm, another class of fireball models has emerged, which we call for simplicity photospheric models (see for example [15-19]). In this class of models the spectrum of a GRB is explained as reprocessed quasi-thermal radiation coming from the photosphere, *i.e.* the surface where radiation and matter decouple, typically after the acceleration of the fireball has ended for thermal acceleration, or possibly during the acceleration phase for magnetic acceleration (which is slower than thermal acceleration). A thermal or quasi-thermal initial spectrum is reprocessed within the jet to produce the non-thermal spectrum commonly observed in GRBs. The differences between the various photospheric models lie in the mechanisms responsible for the reprocessing of the thermal spectrum, which in turn requires different ingredients: strongly magnetized or non-magnetized jets, baryon-dominated or baryon-poor, or other factors.

2. – GRBs as multi-messenger sources

Given the large energy reservoir available, and the particle acceleration mechanisms operating in their jets, GRBs are expected to be sources of neutrinos and Cosmic Rays on top of electromagnetic radiation. In Bustamante *et al.* [2], for example, the authors assume an internal shock model and compute the fraction of energy that goes into each of the 3 messengers, as a function of the internal shock radius R_c (fig. 1). Moreover, short GRBs are thought to be also sources of Gravitational Waves because of their origin from the merger of compact objects. For these reasons, with the advent of neutrino and GW detectors and the refinement of our picture on CR acceleration, GRBs have taken center stage in the new "multi-messenger" astrophysics scene. GRB models, as a result, have started to be constrained by multi-messenger observations.

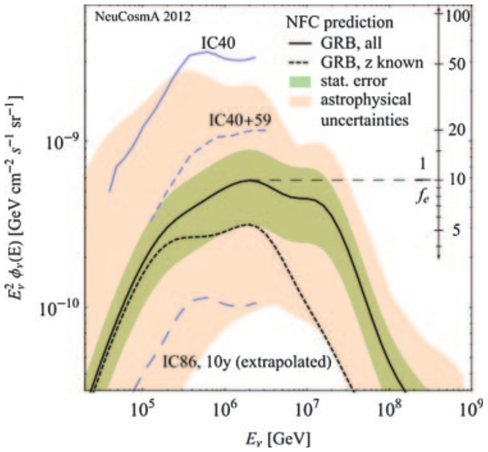

Fig. 2. – Current and predicted future IceCube limits for the neutrino flux from the population of GRBs, compared to the expected flux from the GRB population according to a numerical computation of the fireball model (NFC). The astrophysical uncertainty region is obtained by varying the parameters of the NFC, in particular the variability time scale, the bulk Lorentz factor, the proton injection index, and the energy in electrons *versus* magnetic field (reproduced by permission from Hümmer *et al.*, Physical Review Letters **108** (2012) 231101, copyright (2012) by the American Physical Society [20], `http://dx.doi.org/10.1103/PhysRevLett.108.231101`).

2˙1. *GRBs, Cosmic Rays, and neutrinos.* – GRBs have been proposed as a candidate source for Ultra-High-Energy Cosmic Rays (UHECRs), *i.e.*, cosmic particles with a kinetic energy greater than 10^{18} eV. Indeed, in internal shocks protons are expected to be accelerated alongside electrons, and the Lorentz factor and the efficiency of acceleration inferred for GRBs observed above 100 MeV by *Fermi* LAT allow for CR acceleration up to 10^{20} eV and more. However, GRBs look too rare within the GZK radius to explain the very end of the CR spectrum [21]. In internal shocks, we also expect the production of neutrinos along with CRs. Depending on the characteristics of the jet we could have different scenarios.

- The “neutron model”: protons are confined within the jet by magnetic fields. Cosmic rays are produced by neutrons, produced in the δ^+_{1232} resonance $p\gamma \rightarrow n\pi^+$ or $p\gamma \rightarrow p\pi^0$, which can escape the jet and then β-decay. In this scenario, we expect one neutrino for each cosmic ray, in a 1:1:1 ratio because of flavor mixing.
- Protons are not confined within the jet, and they can escape through the sides. This greatly suppresses the neutrino flux.
- Photohadronic processes are not limited to one per proton, and the production of neutrinos is greatly enhanced.

A simple internal shock model where cosmic rays, neutrinos and γ-rays are all produced in the same zone is excluded by IceCube observations [22]. However, more refined models can be shown to produce a much lower flux [2]. This is shown for example in fig. 2: the current limit is still an order of magnitude above the expected flux from the population of GRBs. However, 10 years of observations of the completed IceCube experiment will constrain strongly the internal shock model of GRBs. Photospheric models are also not yet constrained by the current IceCube limit but will be in the future [23].

2˙2. *Short GRBs and Gravitational Waves.* – The first detection of GW [24] has opened up the era of GW astronomy. The next breakthrough is expected to be the detection of the electromagnetic counterpart of a GW event. The most promising candidate is a nearby short GRB, which is thought to be generated by the merger of two compact objects. The population of short GRBs is closer than the population of long GRBs, and it is expected to be within the reach of the current LIGO horizon. At the same time, full-sky monitors such as *Fermi* GBM or survey hard X-ray telescopes such as Swift/BAT or INTEGRAL/ISGRI are continuously monitoring the high-energy sky hunting for GRBs. The estimate of the expected number of joint detections per year is highly uncertain, ranging from ~ 0.1 to 2 per year for the final sensitivity of Advanced LIGO and VIRGO [25], depending on the average jet opening angle of short GRBs. A joint detection would make a spectacular direct confirmation of the merger model, and provide complementary measurements which would constrain our picture of the central engine as well as the jet in an unprecedented way. For example, the GW signal allows for the measurement of the mass of the two merging compact objects, the luminosity distance, the spins of the compact objects, the orientation and the shape of the orbit during the merger. On the other hand, the electromagnetic measurement would constrain the properties of the jet (magnetic field, Lorentz factor and so on), the astrophysical context (the type of the host galaxy, position within host galaxy) and the distance (redshift). Such joint measurement would, therefore, provide unprecedented data on the merger and greatly constrain our models of the formation of a short GRB. In correspondence of the first GW event, produced by the merger of two large black holes, a weak and short sGRB-like signal was observed in the data of *Fermi* GBM [26]. The significance of the signal, after accounting for trials, was only $2.8\ \sigma$, too low to claim a firm detection. Moreover, Greiner *et al.* [27] found a smaller significance after using a different data selection and different methods. Also, the fluence measured appears to be in tension with the upper limit obtained by INTEGRAL/ACS [28]. If confirmed by future observations, the measurement of a short GRB in correspondence to the merger of two BHs would constitute a surprise, as a BH-BH system is expected to be “clean”, and not to generate any electromagnetic signal. Such an observation would revolutionize both our models of central engines for short GRBs, and our knowledge about BH-BH systems and their environment.

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