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Ultra-high Energy Cosmic Rays and Neutrinos from Gamma-Ray Bursts, Hypernovae and Galactic Shocks☆

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Abstract

I review gamma-ray burst models (GRBs) and observations, and discuss the possible production of ultra-high energy cosmic rays and neutrinos in both the standard internal shock models and the newer generation of photospheric and hadronic GRB models, in the light of current constraints imposed by IceCube, Auger and TA observations. I then discuss models that have been proposed to explain the recent astrophysical PeV neutrino observations, including star-forming and star-burst galaxies, hypernovae and galaxy accretion and merger shocks.

Keywords: Cosmic rays, Neutrinos,

1. Introduction

The origin of the cosmic rays above the knee ($E \gtrsim 10^{15}$ eV) and up to the range of ultra-high energy cosmic rays (UHECRs, 10^{18} eV $\lesssim E \lesssim 10^{21}$ eV) remains a mystery. Attempts at correlating the arrival directions of UHECRs with known AGNs have so far yielded no convincing results [1, 2, 3]. Partly for this reason, other high energy sources, which are distributed among, or connected with, more common galaxies, have been the subject of much interest. These include gamma-ray bursts (GRBs), hypernovae (HNe) and galactic shocks, the latter being due either to accretion onto galaxies (or clusters) or galaxy mergers.

An important clue for the presumed sources of UHECR would be the detection of ultra-high energy neutrinos (UHENUs) resulting from either photohadronic ($p\gamma$) or hadronuclear (pp, pn) interactions of the UHECR within the host source environment and/or during propagation towards the observer. The value of this is of course that neutrinos travel essentially unabsorbed along straight lines (or geodesics) to the observer, thus pointing back at the source. Such interactions leading to neutrinos, arising via charged pions, also result in a comparable number of neutral pions leading to high energy gamma-rays, which are however more prone to subsequent degradation via $\gamma\gamma$ cascades against low energy ambient or intergalactic photons.

The prospect of tagging UHECRs via their secondary neutrinos has recently become extremely interesting because of the announcement by IceCube [4] of the discovery of an isotropic neutrino background (INB) at PeV and sub-PeV energies, which so far cannot be associated with any known sources, but whose spectrum is clearly well above the atmospheric neutrino background, and is almost certainly astrophysical in origin.

☆Based on a talk given at the Origin of Cosmic Rays: Beyond the Standard Model conference in San Vito di Cadore, Dolomites, Italy, 16-22 March 2014. This is not a comprehensive review of the topics in the title; it is weighted towards work in which I have been more personally involved.

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2. Gamma-Ray Bursts

There are at least two types of GRBs [5], the long GRBs (LGRBs), whose γ-ray light curve lasts $2\text{ s} \lesssim t_\gamma \lesssim \text{few} \times 10^3$ s, and the short GRBs (SGRBs), whose light curve lasts $t_\gamma \lesssim 2$ s. The spectra of both peak in the MeV range, with power law extensions below and above the peak of (photon number) slopes $\alpha \sim -1$ and $\beta \sim -2$, the peak energy E_{pk} of the SGRBs being generally harder (few MeV) than those of the LGRBs ($\lesssim$ MeV) [6]. This broken power law spectral shape, known as a Band spectrum, is accompanied in some cases by a lower energy (tens of keV) and less prominent black-body hump, and/or by a second, higher energy power law component, in the sub-GeV to GeV range, whose photon number slope is appreciably harder then the super-MeV β slope, e.g. [7, 8] (Fig. 1).

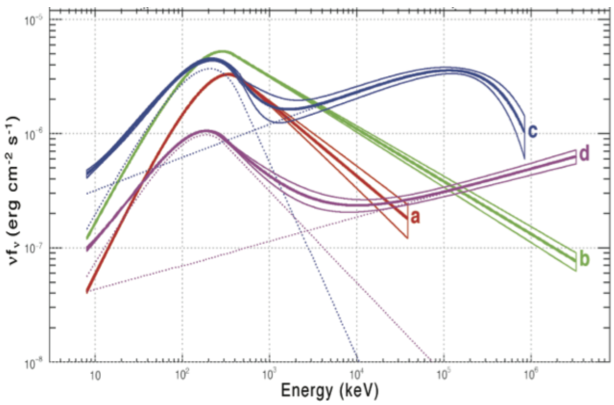

Figure 1: Spectra of GRB090926A observed by the Fermi LAT and GBM instrument, showing the time evolution over four different succesive time bins, the first two of which show a standard (pre-Fermi) broken power law (Band) shape, while the last two show also a second, harder spectral component [9].

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The MeV light curves exhibit short timescale variability down to ms, extensively charted along with the MeV spectra by the CGRO BATSE, the Swift BAT and more recently by the Fermi GBM instruments, while the GeV light curves and spectra have in the last several years been charted by the Fermi LAT instrument, e.g. [7]. An extremely interesting property shown by most of the LAT-detected bursts is that the light curves at GeV energies start with a time lag of several seconds for LGRBs, and fractions of a second for SGRB, relative to the start of the lightcurves at MeV energies, as seen in Fig. 2.

The GeV emission amounts to about 10% and 30-50% of the total energy budget of LGRBs and

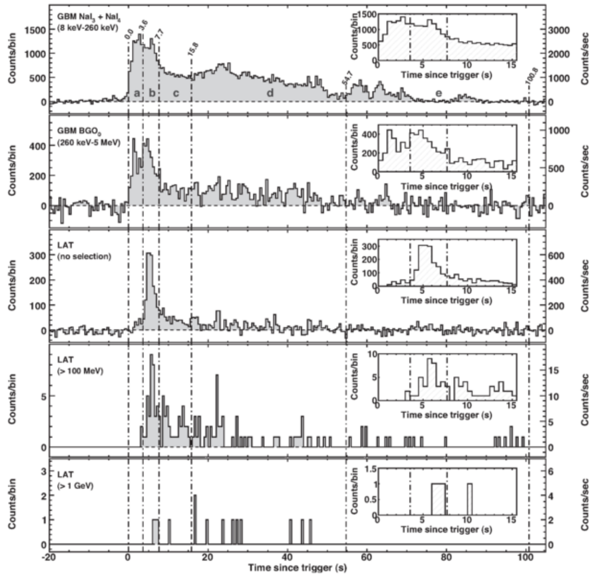

Figure 2: Light curves of GRB080916C with the GBM (top two curves) and LAT (bottom three curves) [10], showing the GeV-MeV relative time lag.

SGRBs respectively, and is detected in roughly 10% of the LGRBs, and in a somewhat larger percentage of SGRBs, although the GeV detection is ubiquitous in the brighter bursts and the non-detections may be due to being below the LAT sensitivity threshold [11].

The huge energies involved in GRB led to the view that it involves a fireball of electrons, photons and baryons which expands relativistically [12, 13, 14, 15, 16, 17], produced by a cataclysmic stellar event. The observational and theoretical work over the past twenty years has resulted in a generally accepted view of LGRBs as originating from the core collapse of massive ($\gtrsim 25M_\odot$) stars [18, 19, 20], whose central remnant quickly evolves to a few solar mass black hole (BH), which for a fast enough rotating core results in a brief accretion episode powering a jet which breaks through the collapsing stellar envelope. This view is observationally well supported, the LGRBs arising in star-forming regions, sometimes showing also the ejected stellar envelope as a broad-line Ic supernova, a "hypernova", whose kinetic energy is $\gtrsim 10^{52}$ erg, an order of magnitude higher than that of an ordinary SN Ic or garden variety supernova.

For SGRBs, the leading paradigm is that they arise from the merger of a compact double neutron star (NS-NS) or neutron star-black hole (NS-BH) binary [13, 16, 17], resulting also in an eventual central BH and a briefer accretion-fed episode resulting in