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 $\leq E \leq 10^{21}$ 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 ($\gamma p$) 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.

$^\dagger$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.
2. Gamma-Ray Bursts

There are at least two types of GRBs [5]. The long GRBs (LGRBs), whose $\gamma$-ray light curve lasts $2 \, \text{s} \lesssim t_p \lesssim \text{few} \times 10^3 \, \text{s}$, and the short GRBs (SGRBs), whose light curve lasts $t_p \lesssim 2 \, \text{s}$. The spectra of both peaks 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 $E_{\text{pk}}$ 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 $\beta$ slope, e.g. [7] (Fig. 1).

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 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 ($\gtrsim 25 M_\odot$) 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 “hypermnova”, whose kinetic energy is $\gtrsim 10^{51}$ 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

![Figure 1: Spectra of GRB090926A observed by the Fermi LAT and GBM instrument, showing the time evolution over four different successive 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 [2].](image1)

![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.](image2)
a jet. Observationally this is supported by the lack of an observable supernova, and by the fact that they are observed both in star-forming and in old population galaxies, often off-set from the optical image, as expected if in the merger the remnant has been kicked off and had time to move appreciably. While the SGRB origin is less firmly established than that of LGRBs, compact mergers are nonetheless widely considered the most likely explanation, which are also of great importance as a guaranteed source of gravitational waves (GWs), being the object of scrutiny by LIGO, VIRGO and other GW detectors.

The MeV radiation providing the detector trigger as well as the slightly delayed GeV radiation are jointly called the prompt emission of the GRB. In a fraction of bursts, a prompt optical flash is also detected by ground-based robotic telescopes [21] or by rapidly slewed multi-wavelength GRB missions such as Swift [22]. The most widely accepted view of the GRB emission is that it is produced by shocks in the relativistic outflows, the simplest example of which are the external shocks where the outflow is decelerated in the external interstellar medium or in the stellar wind of its progenitor [23][24]. In such shocks magnetic field can be amplified, and electrons can be Fermi accelerated into a relativistic power law energy distribution, leading to broken power law spectra peaking initially in the MeV range. Both a forward and reverse shock are expected to be present, the latter producing synchrotron radiation in the optical range, while inverse Compton (IC) radiation in the shocks produces a GeV component [25]. The fast time variability of the MeV light curves is however better explained through what is called the standard internal shock model [26], which addresses the spectrum, or invoking a larger role for the scattering processes [30][34][35], which addresses both the spectrum and efficiency issues. It is worth stressing that the need for such “non standard” internal shocks or photospheres is important (a fact not widely recognized) when considering IceCube neutrino fluxes expected from GRBs.

The Swift satellite launched in 2004 had gamma-ray, X-ray and optical detectors, which revealed new features of the GRB afterglows, including an initial steep decay followed by a flatter decay portion of the X-ray afterglow, interspersed by X-ray spikes, finally blending into the previously known standard power law decay behavior. These features could be represented through the high latitude emission [36], a continued or multi-Lorentz factor outflow, and continued internal shocks, e.g. [37][38].

The Fermi satellite, launched in late 2008 and sensitive between 1 keV \( \leq E \leq 300 \) GeV, extended the MeV studies and opened wide the detailed study of bursts in the GeV band, which can last for \( \approx 10^3 \) s and whose spectra extend in some cases up to \( \sim 100 \) GeV in the source frame. The observed GeV-MeV photon delays from bursts at redshifts \( z \sim 2 \) − 4 led to an interesting constraint on quantum gravity theories, excluding the first order term in \( E/E_{\text{Planck}} \) of the usual effective field theory series expansion formulations [39]. This limit is only reinforced by the presence of additional astrophysical mechanisms for such delays.

In general, the GeV emission of all but the first few time bins is well represented by a forward shock synchrotron radiation [40][41]. This holds also for the brightest GeV bursts ever discovered, GRB130427A.

\[ r_{ph} \approx \left( L \sigma_T / 4 \pi n_e c^3 \eta^3 \right) \sim 4 \times 10^{12} L_{52} n_{ext}^{1/2} \eta_{2.5}^{-3} \text{ cm} \]
\[ r_{fs} \approx \Gamma^2 c t_0 \sim 3 \times 10^{13} \eta_{2.5}^2 t_{10}^{-2} \text{ cm} \]
\[ r_{es} \approx (3E_0/4 \pi n_e c m_p c^2 \eta_{2.5}^{3/2})^{1/3} \sim 2 \times 10^{17} (E_{53}/n_0)^{1/2} \eta_{2.5}^{2/3} \text{ cm} \]
However, the first few time bins of the GeV emission \cite{42} may need to be ascribed to the *prompt* emission, which is also responsible for the MeV emission - for which, as mentioned, a self-consistent analysis must consider models going beyond the standard simple internal shock, c.f. below.

In leptonic models, the prompt MeV emission (and the GeV-MeV delay) can be, and needs to be, explained while avoiding the internal shock spectral and efficiency inconsistencies. This has been done in the framework of both leptonic and hadronic models. Among leptonic ones, for instance, the MeV radiation can arise at smaller radii, e.g. in the photosphere or a cocoon, and upscattering by internal or external shocks further out produce the delayed GeV radiation \cite{43,44}. Alternatively, GeV photons may be created leptonically by pair cascades initiated by MeV photon backscattering \cite{45}. Among hadronic models of the prompt emission, one type of models considers dissipative photospheres as responsible for the MeV photons \cite{43,46}, while the GeV photons are due to $pp, pn$ collisions following from neutron-proton decoupling further out, the GeV $\gamma\gamma$ optical thinness occurring in any case at radii $\gtrsim 10^{15}$ cm, leading to the GeV-MeV delay \cite{46,47}. Another type of alternative to standard internal shocks are the hadronic modified internal shocks, e.g. \cite{49}. In one such model \cite{49}, accelerated hadrons lead to $p\gamma$ secondaries resulting in a slower heating than simple shocks, and re-accelerated secondaries lead to a self-consistent photon spectrum of the correct shape and high radiative efficiency, as well as providing a natural GeV delay.

3. GRB UHE Neutrinos and Cosmic Rays

The pioneering works of \cite{50,51} have served as the basis for most of the thinking on UHE cosmic ray acceleration and VHE neutrino production in GRBs. These first-generation models, as one may call them, were based on a simplified “standard” internal shock (IS) model, where the bulk Lorentz factor $\Gamma \equiv \eta$ and the variability timescale $t_{\nu}$ entering eqn. (1) are either assumed of inferred from $\gamma$-ray observations, the photon spectrum is assumed to be a standard Band function and $p\gamma$ interactions occur via the $\Delta$-resonance. More detailed calculations of a diffuse neutrino flux, still based on this simple IS model but using specific electromagnetically (henceforth: EM) observed bursts serving to calibrate the neutrino to photon (or relativistic proton to electron, $L_\nu/L_\gamma \sim L_p/L_e$) luminosity ratio were made by \cite{52}.

The first IceCube data on GRBs using 40 strings and then 56 strings as the array completion progressed were presented in \cite{54,55,53}. The results using 215 EM-detected GRBs with $\nu_\mu$ fluxes normalized to the $\gamma$-ray fluxes indicated that the diffuse neutrino upper limits were a factor $\sim 5$ below this IS model predictions (Fig. 3), unless the proton to electron ratio was much less than $L_p/L_e \sim 10$. Both this and a model independent analysis using a broken power law photon spectrum with variable break energy and $\Delta$-resonance interaction indicated an inconsistency between the $\nu_\mu$ upper limits and a significant contribution of GRB to the UHE cosmic ray flux observed by Auger and HiRes. This was a very important first cut in constraining models with IceCube.

Subsequent investigations pointed out that the IS model fluxes used for this comparison were overestimated \cite{57,58}. More careful consideration of the $p\gamma$ interaction in this model beyond the $\Delta$-resonance, including multi-pion and Kaon channels with the entire target photon spectrum yielded substantially lower predicted fluxes in the TeV-PeV energy range considered \cite{58}, indicating that $\gtrsim 5$ years of observation with the full 86 string array may be needed to rule out the simple IS model (Fig. 4).

The internal shock radius $r_i$ depends on both the bulk Lorentz factor $\eta$ and the time variability of the outflow $t_{\nu}$, see eq. (1). Both factors also influence the comoving magnetic field in the shock, the photon spectral peak and the photon luminosity, thus affecting the neutrino spectral flux, see Fig. (5).

Another simplification affecting the results is that
the internal shocks in the above were assumed to have a constant radius, whereas they advance and expand with the flow. Calculating numerically such time-dependent IS models which accelerate CRs, including the full range of $p\gamma$ interactions and the observed $\gamma$-ray luminosity function and variability distributions, the current IceCube 40+59 strings $\nu_\mu$ upper limits are in fact compatible with GRBs contributing a significant fraction of the $\sim 10^{20}$ eV UHECR flux [59] (Fig. 6), but the IceCube PeV neutrino flux.

More importantly, the use of the standard internal shock model, which is favored by observers for its simplicity and ease of computation, needs to be reconsidered. This model has been known for the past decade to have problems explaining the low energy $\gamma$-ray spectral slopes and the radiative efficiency [28], and alternatives free of the $\gamma$-ray inconsistencies have been investigated, e.g. photospheric models and modified internal shock models. The neutrino emission of baryonic photosphere models [60, 61] and modified IS models [49] differs qualitatively from that of the standard IS models.

In the case of photospheric models, it is worth stressing that the spectrum is likely to deviate from a blackbody; a non-thermal of broken power law can be produced by dissipative effects, such as subphotospheric scattering [35], inelastic nuclear collisions [47], photospheric shocks or magnetic dissipation [46], etc. The spectrum and luminosity normalization also depend on whether the dynamics of the expansion is dominated by baryonic inertia, in which case the bulk Lorentz factor initially accelerates as $\Gamma = (r/r_0)$ until it reaches the saturation value $\Gamma = \eta$ at the coasting radius $r_{\text{sat}} = r_0\eta^3$; the photospheric radius $r_{ph}$ occurs generally beyond the saturation radius and is given by the first line of eq. (1).

Alternatively the dynamics might be dominated by magnetic stresses. In this case the photospheric radius depends on the value of the magnetization index $\mu$, where $\Gamma(r) = (r/r_0)^\mu$ and $\mu = 1/3$ for extreme magnetic domination, e.g. [46, 58]. For such magnetic cases, the photospheric radius is generally in the accelerating phase $\Gamma \propto r^3$, and is given by

$$r_{ph} = r_0\eta^\mu (\eta r_0)^{1/(1+2\mu)}$$

(2)

where $r_0$ is the launch radius ($\sim 10^7$ cm) and $\eta = \left(L_{\text{c}}/4\pi n_e e^2 c^3 r_0^2(1+3\mu)^2\right)$. Fits to determine the degree of magnetic domination have been done using Fermi GBM and LAT data [62, 63], indicating that a degree of magnetic domination does exist, which differs between bursts. A related point is that if magnetic stresses are significant in a GRB jet, this reduces the
comoving photon density in the jet, allowing heavy nuclei in the jet to survive photo-dissociation [64], a point of interest in view of the Auger [65] data pointing towards a heavy composition of UHECR at high energies.

The diffuse neutrino flux from both baryonic and extreme magnetic photospheric models has been computed (see Fig. 5 [58]), where the extreme magnetic photospheric model is shown as red dashed lines and the baryonic photospheric model as blue dotted lines. They appear compliant with the IceCube 40+59 string upper limits, which however were calculated for a canonical Band spectral shapes, and a more spectral-specific comparison is necessary. This has been done for baryonic photospheres [66], see Fig. 7. As the observations accumulate, these constraints are getting tighter, at least for the simple IS and the simple baryonic photosphere models.

Concerning the IceCube non-detection of the EM brightest burst ever observed, GRB 130427A, a detailed calculation [67] shows that for this particular burst, except for the extreme magnetic photosphere model, the standard IS model, the baryonic photosphere model and a model-independent analysis are compatible with its non-detection.

4. Hypernovae, SFGs/SBGs, Galactic/Cluster Shocks, AGNs as UHECR/UHENU Sources

Hypernovae (henceforth HNe) are Type Ic core collapse supernovae with unusually broad lines, denoting a much higher ejecta velocity component than in usual SNeIc. This indicates a component of the ejecta reaching up to semi-relativistic velocities, with $\Gamma \beta \sim 1$, and a corresponding inferred ejecta kinetic energy $E_{\text{kin}} \sim 10^{52.5}$ erg, one order of magnitude higher than that of normal SNeIc and normal SNe in general [68, 69]. Their rate may be 1%-5% of the normal SNeIc rate, i.e. as much as 500 times as frequent as GRBs [70]. While core collapse (collapsar) type long GRBs appear to be accompanied by HNe, the majority of HNe appear not to have a detected GRB, e.g. [71]. The semi-relativistic velocity component may be due to an accretion powered jet forming in the core collapse, as in GRBs, which only for longer accretion episodes is able to break through the collapsing envelopes, while for shorter accretion episodes it is unable to break out. In both cases the jet accelerates the envelope along the jet axis more forcefully (jet-driven supernova), causing an anisotropic expansion, e.g. [72], whereas in the majority of core collapses a slow core rotation or short accretion times lead to no jet or only weak jets and a “normal” quasi-spherical SNeIc [73].

The dominant fraction of GRB-less HNe, if indeed due to a non-emerging (choked) jet, would be effectively a failed GRB, which could be detected
via a neutrino signal produced in the choked, non-exiting jet, or a neutrino precursor in those collapses where the jet did emerge to produce a successful GRB [74, 75, 76]. Searches with IceCube have so far not found them, e.g. [77, 78].

An interesting aspect of HNe is that the higher bulk Lorentz factor of the ejecta leads to estimates of the maximum UHECR energy accelerated which, unlike for normal SNe, is now in the GZK range,

$$\varepsilon_{\text{max}} \approx ZeB\beta = 4 \times 10^{18} \text{ ZeV}$$ (3)

especially if heavy nuclei (e.g. Fe, Z = 26) are accelerated [79, 80, 81]. The photon field is dilute enough so that the heavy nuclei avoid photodissociation [81, 64]. The HNe kinetic energy and occurrence rate is sufficient then to explain the observed UHECR diffuse flux at GZK energies, without appearing to violate the IceCube upper limits. The HNe, as other core collapse SNe and long GRBs, occur in early type galaxies, with a larger rate in star-forming galaxies (SFGs) and even larger rate in starburst galaxies (SBGs).

Magnetars, another type of high energy source expected from some core collapse supernovae in SFGs and SBGs, are a sub-class of fast-rotating neutron stars with an ultra-strong magnetic field, which have been considered as possible sources of UHECR and UHENUs [82, 83, 84, 85, 86].

SFGs make up $\geq 10\%$ of all galaxies, while SBGs make up $\geq 1 - 3\%$. AGNs make up $\sim 1\%$ of all galaxies, most AGNs being radio-quiet, i.e. without an obvious jet, while radio-loud AGNs (with a prominent jet) represent $\sim 0.1\%$ of all galaxies. Radio-loud AGNs have long been considered possible UHECR and UHENU sources, e.g. [87, 88]. However, the lack of an angular correlation between Auger or TA UHECR events and AGNs [11, 12] may be suggesting that more common galaxies, e.g. SFGs or SBGs, may be hosting the UHECR sources, which could be HNe, GRBs or magnetars, all of which appear capable of accelerating UHECRs at a rate sufficient to give the observed diffuse UHECR flux.

Another possibility is that UHECR are accelerated in shocks near the core of radio-quiet AGNs, where they would produce UHENUs [89, 90, 91], or alternatively UHECR could be accelerated in stand-off shocks caused by the inflow of intergalactic gas onto clusters of galaxies [92, 93, 94]. Galactic merger shocks (GMSs) also appear capable of accelerating UHECR, with a similar energy input rate into the IGM [95]; see below.

5. The PeV Neutrino Background

In 2013 the IceCube collaboration announced the discovery of the first PeV and sub-PeV neutrinos which, to a high confidence level, are of astrophysical origin [96]. The majority of these are cascades, whose angular resolution is $15 - 30\degree$, ascribed to $\nu_e, \bar{\nu}_e$, while a minority are Cherenkov tracks with an angular resolution $\sim 1\degree$ due to $\nu_\mu, \bar{\nu}_\mu$. Their spectrum stands out above that of the diffuse atmospheric spectrum by at least $4.1\sigma$, with a best fit spectrum $\propto E^{-2.2}$. There is no statistically significant evidence for a concentration either towards the galactic center or the galactic plane, being compatible with an isotropic distribution. No credible correlation has been so far established with any well-defined extragalactic objects, such as AGNs, but the working assumption of an extragalactic origin is widely accepted.

A flux of PeV neutrinos from starburst galaxies at a level close to that observed level was predicted by [97]. The actual accelerators could be hypernovae; the maximum energy of protons, from eq. (3), is sufficient for the $pp$ production of PeV neutrinos [98], and statistically, $\mathcal{O}(1)$ of the observed events could be due to a hypernova (or at most a few) located in the bulge of the Milky Way. However, the bulk of the observed events must come from an isotropic distribution, and hypernovae in ultra-luminous infrared galaxies (ULIRGs) or SFGs/SBGs could be responsible [99, 100].

![Image](https://example.com/image.png)

Figure 8: The INB flux (right) and IGB flux (left) allowed by $pp$ scenarios [101] for a proton slope $p = -2$ (thick dashed) and $p = -2.18$ (thick dashed). The shaded rectangle is the Icecube PeV data [1], while the data points on the left are the Fermi [102] isotropic gamma background data.
More generally \cite{101}, one can ask whether hadronuclear (pp) interactions may be responsible for this isotropic neutrino background (INB) at PeV energies, without violating the constraints imposed by the isotropic gamma-ray background (IGB) \cite{102} measured by Fermi. As shown by \cite{101}, this requires the accelerated protons to reach at least $\sim 100$\,PeV and to have an energy distribution $\propto E^{-p}$ with an index no steeper than $-2.2 \leq p \leq 2.0$ (Fig. 3). An important point is that most events are cascades, involving electron flavor neutrinos, and the $\nu_e$, $\nu_x$ cross section is resonant at CM energies comparable to the $W$ meson mass (Glashow resonance), at around 6.3 PeV in the lab frame. Since events are not seen at this energy, they would be expected if the proton (and neutrino) slopes were $\sim -2.2$, one concludes that the proton distribution steepens or cuts off at energies $\gtrsim 100$ PeV. Such a cutoff may be expected in scenarios where the acceleration occurs in galaxy cluster shocks or in SFG/SBGs, where this energy may correspond to that where the escape diffusion time out of the acceleration region becomes less than the injection time or the $\nu p$ time \cite{101}. Broadly similar conclusions are reached by \cite{99,100,103,104}.

Suggestively, \cite{104} find a weak correlation between five known SFGs (M82, NGC253, NGC4945, SMC and IRAS18293) and the very wide, $15 - 30^\circ$ error boxes of some cascade events, but not correlation so far with any track events; they estimate that 10 years may be needed with IceCube to find track correlations with SFGs at $\gtrsim 99\%$ confidence level.

Another type of large scale shocks in galaxies are the galaxy merger shocks (GMSs), which occur every time two galaxies merge. Every galaxy merged at least once during the last Hubble time, and probably more then once; in fact mergers are the way galaxies grow over cosmological time. Such galaxy mergers were considered in the PeV neutrino background context by \cite{95}. They estimate that individual major mergers involving galaxies with $M \gtrsim 10^{11}M_\odot$ have an average kinetic energy of $E_{\text{kin}} \sim 10^{58.5}$ erg, occurring at a rate $R \sim 10^{-4}\text{Mpc}^{-3}\text{Gyr}^{-1}$, with a relative shock velocity $v_s \sim 10^{10}\text{cm s}^{-1}$. For a CR acceleration fraction $\eta_{\text{cr}} \sim 10^{-1}$ the UHECR energy injection rate into the Universe is $Q_{\text{cr},\text{gms}} \sim 3 \times 10^{44}\text{ergMpc}^{-3}\text{yr}^{-1}$ (which is also the observationally inferred rate UHECR energy injection rate), with a maximum CR energy of $E_{\text{cr,max}} \sim 10^{38}\text{Z eV}$. The $pp$ interactions in the shocks and in the host galaxies lead to PeV neutrinos and $\lesssim 100$ GeV $\gamma$-rays (Fig. 9).

Individual GMSs from major mergers at $z \sim 1$ would yield in IceCube on average $\sim 10^{-2}$ muon events/year, or an isotropic neutrino background (INB) of $\sim 20 - 30\%$ of the IceCube observed PeV-sub-PeV flux. Minor mergers, whose rate is more uncertain, might contribute up to 70-100\% of the INB (Fig. 9). The $\gamma$-ray flux from individual GMS expected is $\sim 10^{-13}\text{erg cm}^{-2}\text{s}^{-1}$, possibly detectable by the future CTA, while the corresponding isotropic gamma background (IGB) is $\sim 10^{-8}\text{GeV cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$, about 20-30\% of the observed Fermi IGB, or a somewhat larger percentage due to minor mergers \cite{95}.

6. Conclusion, Prospects

In conclusion, the sources of UHECR and the observed extragalactic UHENU are still unknown. For UHECR, an exotic physics explanation is almost certainly ruled out, mainly because any such mechanisms would produce a high energy photon component in UHECR which can be observationally ruled out, e.g. \cite{105}. Anisotropy studies from Auger, which initially suggested a correlation with AGNs \cite{106} have more recently, together with Telescope Array observations, yielded no significant correlation with any specific types of galaxies \cite{11,2,18}. This might favor some of the more common types of
galaxies, such as possibly radio-quiet AGNs, or alternatively stellar type events such as GRBs, hypernovae or magnetars, as discussed in §§2,3.

The indications for a heavy UHECR composition at higher energies \[65, 107, 108\] would appear to disfavor AGN jets, where the composition is closer to solar, and favor evolved stellar sources, such as GRBs, hypernovae and magnetars, where a heavy composition is more natural, if the nuclei can avoid photo-dissociation (§4). These sources would also reside in more common galaxies, avoiding the anisotropy constraints.

The PeV and sub-PeV neutrinos discovered by IceCube \[96, 4\] are an exciting development in the quest for finding the neutrino smoking gun pointing at UHECR sources, even if not at the highest energies. Standard IS GRBs appear to be ruled out as the sources for this observed diffuse neutrino flux, given the upper limits for GRBs from IceCube \[55, 53\]. Note however that these limits were obtained for simplified internal shock models, and more careful comparison needs to be made to more realistic models (see §2). Nonetheless, the normal high luminosity, electromagnetically detected GRBs, even if able to contribute to the GZK end of the UHECR distribution \[59\], appear inefficient as PeV neutrino sources. It is possible that low luminosity GRBs (in the electromagnetic channel) could yield appreciable PeV neutrinos \[109\], and also choked GRBs \[76\] would be electromagnetically non-detected but might provide significant PeV neutrino fluxes. The fluxes, however, remain uncertain.

More attractive candidates for the PeV neutrinos are the star-forming and starburst galaxies, hosting an increased rate of hypernovae, or accretion shocks onto galaxies or clusters, or else galaxy mergers, all of which are capable of accelerating CRs up to \(\sim 100\) PeV and produce PeV neutrinos via pp interactions is discussed in §4.

It is also remarkable that the PeV neutrino flux is essentially at the Waxman-Bahcall (WB) bound level \[51, 111\] for UHECR near the GZK range, which is also comparable to the GeV range CR flux \[110\]. Fig. 10. This suggests the intriguing prospect that the same sources may be responsible for the entire GeV-100 EeV energy range, a possibility whose testing would require much further work.

We can look forward to much further progress with continued observations from IceCube, Auger, TA and their upgrades, as well as HAWC, CTA and ground-based Cherenkov arrays and other instruments. UHECR composition and UHECR/UHENU clustering will provide important clues, as well as GeV and TeV photon observations to provide much needed additional constraints, especially if UHENU source localization is achieved.

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