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High-Energy cosmic rays and neutrinos from gamma-ray bursts(*)

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Summary. — A complete model for the origin of high-energy ($\gtrsim 10^{14}$ eV) cosmic rays from gamma-ray bursts (GRBs) and implications of this hypothesis are described. Detection of high-energy neutrinos from GRBs provide an unambiguous test of the model. Evidence for cosmic-ray acceleration in GRBs is suggested by the detection of anomalous γ-ray components such as that observed from GRB 941017. Neutron β-decay halos around star-forming galaxies such as the Milky Way are formed as a consequence of this model. Cosmic rays from GRBs in the Galaxy are unlikely to account for the $\sim 10^{18}$ eV cosmic-ray excess reported by the Sydney University Giant Air Shower Recorder (SUGAR), but could contribute to past extinction events.

PACS 96.40.Tv – Cosmic ray neutrinos and muons.
PACS 98.70.Rz – γ-ray sources; γ-ray bursts.
PACS 98.70.Sa – Cosmic rays including sources, origin, acceleration, and interactions.
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1. – Introduction

One of the outstanding questions in contemporary astronomy is the origin of high-energy cosmic rays (HECRs) ranging from below the knee of the cosmic-ray spectrum at $\approx 3 \times 10^{15}$ eV to the highest energies exceeding 10^{20} eV. Ultra-high energy cosmic rays (UHECRs), defined here as cosmic rays (CRs) with energies greater than the ankle energy at $\approx 5 \times 10^{18}$ eV, are probably extragalactic protons in view of their large gyroradii, lack of enhancements of arrival directions toward the galactic plane, the observed flattening of the cosmic-ray spectrum at the ankle (which could result from photopair energy-loss processes on cosmic-ray protons [1, 2]), and suggestions of a composition change from heavy to light nuclear composition above $\approx 10^{17.4}$ eV [3] (see [4] for a review).

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Because high-energy protons will radiate γ-ray photons from hadronic and leptonic processes at the site where they are produced, the most likely candidate sources of UHECRs are extragalactic nonthermal γ-ray emitters, specifically GRBs and blazar AGNs. Models for these sources involve jets of relativistic plasma that are ejected by accreting black holes. The paucity of blazar sources within tens of Mpc that could account for the near isotropy of cosmic rays at energies $\gtrsim 5 \times 10^{19}$ eV suggest that GRBs are the sources of UHECRs. GRBs in the Galaxy will also accelerate HECRs, and could form most of the cosmic rays with energies between $\approx 10^{14}$ eV and $\approx 5 \times 10^{17}$ eV.

Several types of observations can test this hypothesis. Detection of high-energy neutrinos from a GRB, which would require an ultra-relativistic hadronic component that is much more powerful than the nonthermal electron component that produces the hard X-ray and soft γ-ray emissions from GRBs [7], is predicted by this model. Another prediction is the detection of hadronic emission components in the spectra of GRBs. The unusual γ-ray emission component observed [5] in GRB 941017, which could be caused by ultra-relativistic hadron acceleration and photopion processes in the inner jets of GRBs [6], could be the first example of such a signature.

A third observation that would implicate GRBs as the sources of HECRs is the detection of high-energy neutron β-decay halos around star-forming galaxies [8], including β-decay emission from GRBs in the Milky Way [9]. A fourth observation is the absence of $\gtrsim 10^{18}$ eV cosmic-ray *point-source* excesses, such as the source claimed to be detected with the SUGAR array. This is opposite to the conclusion arrived by [10], as explained below, and will soon be tested with the Auger experiment, which is now taking data.

2. – Complete model for cosmic ray origin

We have recently proposed a model for HECRs from galactic and extragalactic GRBs [1], building on previous suggestions that UHECRs are accelerated by extragalactic GRBs [11-13]. In our model, relativistic outflows in GRBs are assumed to inject power law distributions of cosmic rays to the highest ($\gtrsim 10^{20}$ eV) energies. A diffusive propagation model for HECRs from a single recent GRB within ≈ 1 kpc from Earth that took place within the last 0.5 million years can explain the KASCADE data for the CR ion spectra near and above the knee. The CR spectrum at energies $\gtrsim 10^{18}$ eV is fit with CRs from extragalactic GRBs.

UHECRs produced by extragalactic GRBs lose energy from momentum redshifting and photo-pair and photo-pion production on the CMBR during propagation through a flat ΛCDM universe (we take $\Omega_{matter} = 0.3$ and $\Omega_\Lambda = 0.7$ in our calculations). Attenuation produces features in the UHECR flux at characteristic energies $\sim 4 \times 10^{18}$ eV and $\sim 5 \times 10^{19}$ eV due to photo-pair and photo-pion energy-loss processes, respectively, from distant sources at $z \gtrsim 1$.

The GRB rate-density evolution is assumed to follow the SFR history derived from the blue and UV luminosity density of distant galaxies. To accommodate uncertainty in the SFR evolution, we take two models, one based on optical/UV measurements without extinction corrections (lower SFR), and the other with extinction corrections (upper SFR). The upper SFR is roughly a factor of 3(10) greater than the lower SFR at redshift $z = 1(2)$. For $\gtrsim 10^{19}$ eV CRs, both evolution models give the same flux, but the upper SFR contributes a factor ~ 3 more CR flux over the lower SFR at energies $\lesssim 10^{18}$ eV.

The combined KASCADE, HiRes-I and HiRes-II Monocular data between $\approx 2 \times 10^{16}$ eV to 3×10^{20} eV are fit in fig. 1 which shows our best case, with cosmic-ray

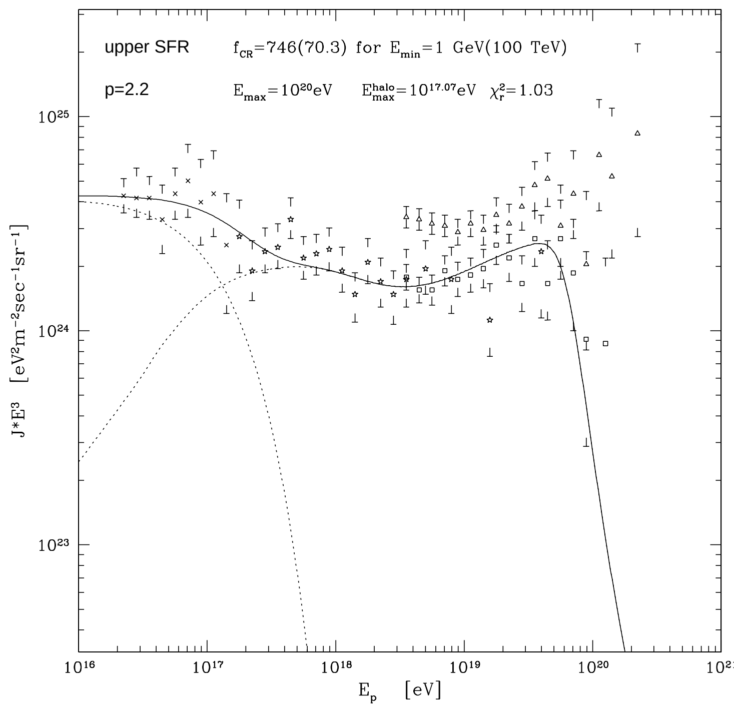

Fig. 1. – Best fit to the KASCADE (crosses), HiRes-I Monocular (squares), and HiRes-II Monocular (stars) data assuming a spectral cutoff at the source of $E_{max} = 10^{20}$ eV and using the upper limit to the SFR evolution. We also show the AGASA data (triangles), but do not include these in our fits (see [1] for references to the data). The cutoff energy for the galactic-halo component is $E^{halo}_{max} = 10^{17.07}$ eV and $\chi^2_r = 1.03$. The fit implies that the transition from Galactic to extragalactic CRs occurs near the second knee and that the ankle is associated with photo-pair production.

number injection index $p = 2.2$, $E_{max} = 10^{20}$ eV, and the upper SFR. A $p = 2.0$ spectrum provides a worse fit than the $p = 2.2$ case, although the CR energy demand is less in this case because CRs are injected equally per unit decade in particle energy. The transition between galactic and extragalactic CRs is found in the vicinity of the second knee at $\approx 10^{17.6}$ eV, consistent with a heavy-to-light composition change [3]. The ankle, at $\approx 10^{18.5}$ eV, is interpreted as a suppression from photo-pair losses, analogous to the GZK suppression.

3. – High-energy neutrinos

By normalizing the energy injection rate to that required to produce the CR flux from extragalactic sources observed locally, we determine the amount of energy a typical GRB must release in the form of nonthermal hadrons. Our results imply that GRB blast waves are baryon-loaded by a factor $f_{CR} \gtrsim 60$ compared to the primary electron energy that is inferred from the fluxes of hard X-rays and soft γ rays measured from GRBs.

In fig. 2 we show the neutrino fluences expected in the collapsar GRB scenario from a burst with photon fluence $\Phi_{rad} = 3 \times 10^{-4}$ erg cm^{-2}. The neutrino fluences are

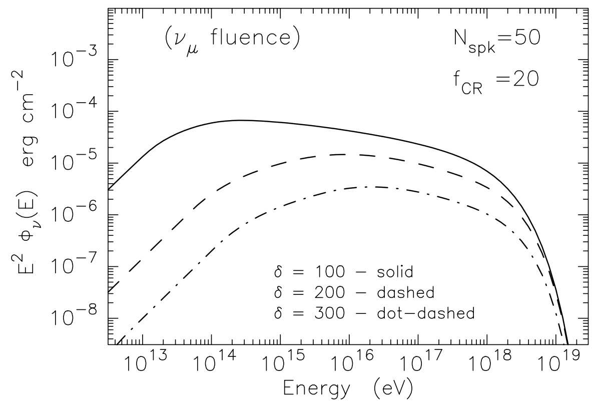

Fig. 2. – The fluences of muon neutrinos calculated for a GRB at $z = 1$ with X-ray/ MeV γ-ray fluence of 3×10^{-4} ergs cm^{-2} and Doppler factors $\delta = 100$, 200 and 300, and a nonthermal baryon-loading factor $f_{CR} = 20$.

calculated for 3 values of the Doppler factor δ from a GRB at redshift $z = 1$ (we take a Hubble constant of 65 km s^{-1} Mpc $^{-1}$ in the calcuations). In order to demonstrate the dependence of the neutrino fluxes on δ, we consider 3 values of δ and set $f_{CR} = 20$ in this calculation. We assume that the prompt emission is contributed by $N_{spk} = 50$ spikes with characteristic timescales $t_{spk} \simeq 1$ s each, which defines the characteristic size (in the proper frame) of the emitting region associated with each individual spike through the relation $R'_{spk} \simeq t_{spk}\delta/(1 + z)$.

The numbers of muon neutrinos that would be detected from a single GRB with these parameters with IceCube for $\delta = 100$, 200 and 300 are $N_\nu = 1.32$, 0.105 and 0.016, respectively. We should note, however, that for the assumed value of f_{CR}, the calculated total fluence of neutrinos (both ν_μ and ν_e) produced when $\delta = 100$ is $\Phi_{\nu,tot} = 7.2 \times 10^{-4}$ erg cm^{-2}, *i.e.,* by a factor $7.2/3 = 2.4$ *larger* than the assumed radiation fluence. This means that the maximum value of the baryon loading that could be allowed if the high-energy radiation fluence is less than the X/γ fluence for this particular case should be about $8 - 10$, instead of 20, in order that the hadronic cascade γ-ray flux is guaranteed not to exceed the measured photon flux. Consequently, the expected number of neutrinos for $\delta = 100$ should be reduced to $\simeq 0.6$. On the other hand, the neutrino fluence for the case $\delta = 200(300)$ is equal to $\Phi_{\nu,tot} = 1.4 \times 10^{-4}(3 \times 10^{-5})$ erg cm^{-2}, so this accommodates an increased baryon-loading from $\lesssim 20$ up to $f_{CR} \simeq 45(200)$, with the expected number of neutrinos observed by IceCube being $N_{\nu,corr} \simeq 0.23(0.16)$. If the radiation fluence at MeV – GeV energies is allowed to exceed the X/γ fluence by an order of magnitude, a possibility that GLAST will resolve, then the expected number of detected neutrinos could be increased correspondingly.

For the large baryon load required for the proposed model of HECRs, calculations show that 100 TeV – 100 PeV neutrinos could be detected several times per year from all GRBs with kilometer-scale neutrino detectors such as IceCube [7, 1]. Detection of even 1 or 2 neutrinos from GRBs with IceCube or a northern hemisphere neutrino detector will provide compelling support for this scenario for the origin of high-energy and UHE cosmic rays.

4. – Hadronic emission components in GRB spectra

Based on joint analysis of BATSE Large Area Detector and the EGRET Total Absorption Shower Counter data, González *et al.* [5] reported the detection of an anomalous MeV emission component in the spectrum of GRB 941017 that decays more slowly than the prompt emission detected with the LAD in the ≈ 50 keV – 1 MeV range. The multi-MeV component lasts for $\gtrsim 200$ seconds (the t_{90} duration of the lower-energy prompt component is 77 s), and is detected with the BATSE LAD near 1 MeV and with the EGRET TASC between ≈ 1 and 200 MeV. The spectrum is very hard, with a photon number flux $\phi(\epsilon_\gamma) \propto \epsilon_\gamma^{-1}$, where ϵ_γ is the observed photon energy.

This component is not predicted or easily explained within the standard leptonic model for GRB blast waves, though it possibly could be related to Comptonization of reverse-shock emission by the forward shock electrons [14], including self-absorbed reverse-shock optical synchrotron radiation [15]. Another possibility is that hadronic acceleration in GRB blast waves could be responsible for this component.

We have argued [6] that this component could be a consequence of the acceleration of hadrons at the relativistic shocks of GRBs. A pair-photon cascade initiated by photo-hadronic processes between high-energy hadrons accelerated in the GRB blast wave and the internal synchrotron radiation field produces an emission component that appears during the prompt phase, as shown in fig. 3. Photomeson interactions in the relativistic blast wave also produce a beam of UHE neutrons, as proposed for blazar jets [16]. Subsequent photopion production of these neutrons with photons outside the blast wave will produce a directed hyper-relativistic electron-positron beam in the process of charged pion decay and the conversion of high-energy photons formed in π^0 decay. These energetic leptons produce a synchrotron spectrum in the radiation reaction-limited regime extending to $\gtrsim$ GeV energies, with properties in the 1–200 MeV range similar to that measured from GRB 941017. GRBs displaying these anomalous γ-ray components are most likely to be detected as sources of high-energy neutrinos [17].

5. – Neutron β-decay halos

If GRBs are the sources of HECRs, then high-energy neutrons will be formed at the burst site through photo-pion processes and, being neutral, can escape to intergalactic space. Indeed, it is possible that charged ultra-high energy protons and ions are trapped by ambient magnetic field and lose energy adiabatically near the acceleration site, so that UHECRs are made primarily of neutron-decay protons.

The decay of the neutrons far from the GRB through the process $n \to p + e^- + \bar{\nu}_e$ leads to β-decay electrons that make synchrotron and Compton radiation. The best prospect for discovering neutron-decay halos is to search for diffuse optical synchrotron halos surrounding field galaxies that display active star formation [8]. GRBs that have recently taken place in our Galaxy will produce Compton radiation at TeV energies that could be detected by the *HESS* and *VERITAS* imaging air Cherenkov telescopes [9]. The emission of nonthermal synchrotron and Compton radiation from photopion processes by UHECRs traveling through intergalactic space will also produce a nonthermal component of the diffuse radiation background, which can be used to determine the magnetic field of intergalactic space.

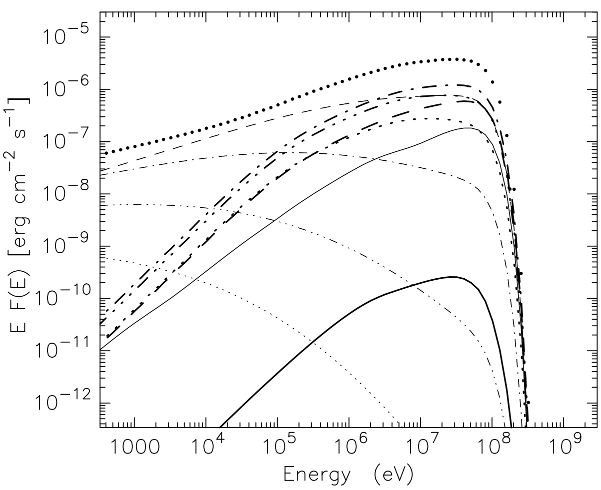

Fig. 3. – Photon energy fluence from an electromagnetic cascade initiated by photopion secondaries in a model GRB, with parameters given in ref. [6]. Five generations of Compton (heavy curves) and synchrotron (light curves) are shown. The first through fifth generations are given by solid, dashed, dot-dashed, triple-dot–dashed, and dotted curves, respectively. The total cascade radiation spectrum is given by the upper bold dotted curve.

6. – GRBs in the Galaxy

Because the Milky Way is actively making young high-mass stars, GRBs will also occur in our Galaxy. The rate of GRBs in the Milky Way is very uncertain because of lack of precise knowledge about the opening angle of GRB jets, but could be as frequent as once every 10000 years. Over the age of the Galaxy, there is a good chance that a nearby powerful GRB with a jet oriented towards Earth could have lethal consequences for life. It has recently been argued [18] that such an event contributed to the Ordovician extinction event 440 Myrs ago.

To assess cosmic ray transport from a GRB, we [19] developed a 3D propagation model to simulate the sequence of irradiation events that occurs when a GRB jet is pointed towards Earth. The cosmic rays move in response to a large-scale magnetic field that traces the spiral arm structure of the Galaxy, and they diffuse through pitch-angle scattering with magnetic turbulence. The magnetic field of the Galaxy is modeled as a bi-symmetric spiral for the Galaxy's disk, and a dipole magnetic field for the Galaxy's halo [20]. The evolution of the particle momentum is found by solving the Lorentz force equation. A Monte Carlo simulation of pitch-angle scattering and diffusion was developed that takes into account the energy dependence of the cosmic-ray mean free path.

Figure 4 displays the cosmic-ray halo that surrounds a GRB source 14000 years after the GRB event. The geometry of the system is modeled by twin radial jets of cosmic rays with a jet-opening half-angle of 0.1 radian. A conical shell forms as a result of protons and neutron-decay protons with energies $\gtrsim 10^{18}$ eV.

The hypothesis [10] that the $\gtrsim 10^{18}$ eV cosmic-ray excesses detected with the AGASA (Akeno Giant Air Shower Array) and SUGAR arrays [21,22] are cosmic-ray neutrons from a GRB is not, however, supported by our simulations. The relativistic blast waves in a GRB accelerate the highest energy cosmic rays over timescales of weeks or less [23], and

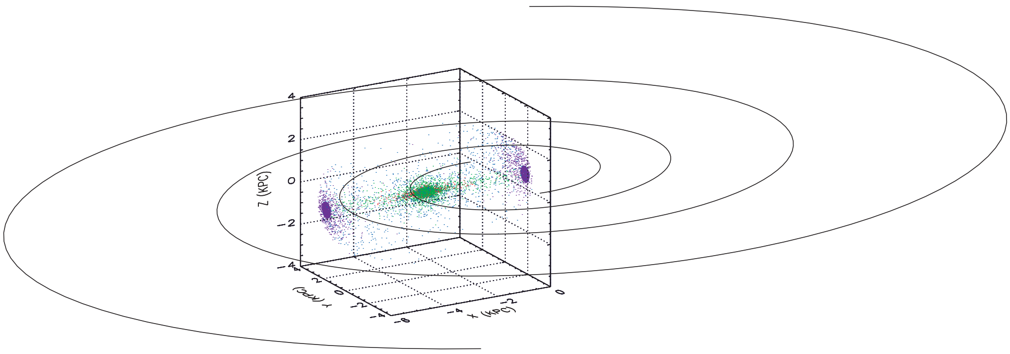

Fig. 4. – Cosmic-ray halo formed 14000 years after a GRB, with radial jets oriented along the galactic plane, that took place at 3 kpc from the center of the Galaxy. For clarity, equal numbers of cosmic rays are injected per decade between 10^{16} – 10^{20} eV.

the high-energy neutrons therefore arrive on this same timescale. Cosmic ray protons with energies $\sim 10^{19}$ eV are delayed over a timescale $\approx 10000\,\theta^3/B_{\mu\mathrm{G}}$ years from a source at the distance of the Galactic Center. For the SUGAR excess, which is coincident on the sub-degree angular scale with a point source, a GRB would have to take place within weeks of the observation for cosmic-ray protons to maintain their direction to the source. Including the requirement that the GRB jet was also pointed towards Earth means that an impulsive GRB origin is excluded because such an event is so improbable. The greater ($\approx 10°$) extent of the AGASA excess does not conclusively exclude a GRB origin, but here the diffuse excess could simply reflect the greater pathlength for cosmic-ray proton collisions with spiral arm gas along the Cygnus arm.

Because the SUGAR point source does not admit an impulsive GRB solution, only cosmic rays from a persistent source, such as a microquasar, could make such an excess. The hypothesis [8, 1] that GRBs are sources of $\gtrsim 10^{14}$ eV cosmic rays is therefore incompatible with such a source. Our cosmic-ray origin hypothesis will soon be tested by results from the Auger Observatory ([1]) to confirm or refute the existence of the SUGAR source. If the source is real, then our GRB/cosmic-ray model is incomplete.

7. – Conclusions

We have summarized a complete model [1] for HECRs from galactic and extragalactic GRBs. Our interpretation of the HECR spectrum requires that GRBs are hadronically dominated, which is necessary [7] for neutrinos from GRBs to be detectable with a km-scale neutrino telescope. Detection of high-energy neutrinos from GRBs will provide strong support for this model.

Searches for anomalous γ-ray emission components with *GLAST*, as already observed form GRB 941017 with BATSE and EGRET, will give additional support for cosmic-ray acceleration in GRBs, provided that these components can be attributed to hadronic cascade radiation [6]. Observations of neutron β-decay radiation from recent GRBs in the Galaxy [9] and around galaxies that host GRBs [8] provide further tests of the hypothesis that high-energy cosmic rays are accelerated by GRBs.

([1]) www.auger.org

The ground-based Auger experiment, which will measure air showers and nitrogen fluorescence from the UHECR interactions in the atmosphere, is now taking data. This experiment will greatly expand our knowledge of high-energy cosmic rays, for example, by measuring with high-quality statistics and checks on calibration the spectrum of $\gtrsim 10^{20}$ eV cosmic rays which produce high-energy neutrinos at their source and as they propagate through intergalactic space. Detection of $\approx 10^{18}$ eV cosmic-ray point sources is incompatible with an origin from impulsive GRBs, so that if the SUGAR source is confirmed, this cosmic-ray origin model is incomplete.

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