An absence of neutrinos associated with cosmic-ray acceleration in γ-ray bursts

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Very energetic astrophysical events are required to accelerate cosmic rays to above 10^{18} eV electronvolts. GRBs (γ-ray bursts) have been proposed as possible candidate sources. In the GRB 'fireball' model, cosmic-ray acceleration should be accompanied by neutrinos produced in the decay of charged pions created in interactions between the high-energy cosmic-ray protons and γ-rays. Previous searches for such neutrinos found none, but the constraints were weak because the sensitivity was at best approximately equal to the predicted flux. Here we report an upper limit on the flux of energetic neutrinos associated with GRBs that is at least a factor of 3.7 below the predictions. This implies either that GRBs are not the only sources of cosmic rays with energies exceeding 10^{18} eV or that the efficiency of neutrino production is much lower than has been predicted.

Neutrinos from GRBs are produced in the decay of charged pions produced in interactions between high-energy protons and the intense γ-ray background within the GRB fireball, for example in the A∗ → pν̄μνμ decay. When these pions decay via π^+ → μ^+ν̄μ and μ^+ → e^+ν̄e, they produce a flux of high-energy muon and electron neutrinos (νμ, νe), coincident with the γ-rays, and peaking at energies of several hundred TeV. Such a flux should be detectable using km^3-scale instruments like the IceCube neutrino telescope (Supplementary Fig. 1). Owing to maximal mixing between muon and tau neutrinos, neutrinos from pion decay in and around GRBs will arrive at Earth in an equal mixture of flavours. We focus here only on muons produced in νμ charged-current interactions. As the downgoing cosmic-ray muon background presents challenges for the identification of neutrino-induced muons, we achieve our highest sensitivity for upgoing neutrinos (from sources in the southern sky). However, the tight constraint of spatial and temporal coincidence with a GRB allows some sensitivity even in the southern sky. One of the two analyses presented here therefore includes Southern Hemisphere GRBs during the 2009–10 IceCube run.

The results presented here were obtained while IceCube was under construction, using 40 and 59 of the 86 photomultiplier strings of the final detector (Supplementary Fig. 1), which took data from April 2008 to May 2009 and from May 2009 until May 2010, respectively. During the 59-string data-taking period, 190 GRBs were observed and reported by γ-ray observatory satellites via the GRB Coordinates Network, with 105 in the northern sky. Of those GRBs, 9 were not included in our catalogue owing to detector downtime associated with background suppression. Two additional GRBs were included from test runs before the start of the official 59-string run. 117 northern-sky GRBs were included from the 40-string period to compute the final combined result. GRB positions were taken from the satellite with the smallest reported error, which is typically smaller than the IceCube resolution. The GRB γ-ray emission start (Tstart) and stop (Tstop) times were taken by finding the earliest and latest time reported for γ-ray emission.

As in our previous study, we conducted two analyses of the IceCube data. In a model-dependent search, we examine data during the period of γ-ray emission reported by any satellite for neutrinos with the energy spectrum predicted from the γ-ray spectra of individual GRBs. The model-independent analysis searches more generically for neutrinos on wider timescales, up to the limit of sensitivity to small numbers of events at ±1 day, or with different spectra. Both analyses follow the methods used in our previous work, with the exception of slightly changed event selection and the addition of the Southern Hemisphere to the model-independent search. Owing to the large background of downgoing muons from the southern sky, the Southern Hemisphere analysis is sensitive mainly to higher-energy events (Supplementary Fig. 3). Systematic uncertainties from detector effects have been included in the reported limits from both analyses, and were estimated by varying the simulated detector response and recomputing the limit, with the dominant factor being the efficiency of the detector’s optical sensors.

In the 59-string portion of the model-dependent analysis, no events were found to be both on-source and on time (within 10 s of a GRB and between Tstart and Tstop). From the individual burst spectra, with an assumed ratio of energy in protons to energy in electrons (z/p = 10) (ref. 6), 8.4 signal events were predicted from the combined 2-year data set and a final upper limit (90% confidence) of 0.27 times the predicted flux can be set (Fig. 1). This corresponds to a 90% upper limit on z/p of 2.7, with other parameters held fixed, and includes a 6% systematic uncertainty from detector effects.

In the model-independent analysis, two candidate events were observed at low significance, one 30 s after GRB 091026A (event 1) and another 14 h before GRB 091230A (most theories predict neutrinos within a few minutes of the burst). Subsequent examination showed they had both triggered several tanks in the IceTop surface air shower array, and are thus very probably muons from cosmic-ray air showers. In Fig. 2, we are shown limits from this analysis on the normalization of generic power-law muon neutrino spectra expected from shock acceleration at Earth as a function of the size of the time window Δt, which is the difference between the neutrino arrival time and the first reported satellite trigger time. As a cross-check on both results, the limit from this analysis on the average individual burst spectra during the time window corresponding to the median duration of the bursts in the sample (28 s) was 0.24 times the predicted flux, within 10% of the model-dependent analysis.

Assuming that the GRBs in our catalogue are a representative sample of a total of 667 per year (ref. 7), we can scale the emission from our catalogue to the emission of all GRBs. The resulting limits can then be compared to the expected neutrino rates from models that assume that GRBs are the main sources of ultra-high-energy cosmic rays, with sampling biases of the same order as model uncertainties in the flux predictions. Limits from the model-independent analysis on fluxes of this type are shown in Fig. 3.

These limits exclude all tested models with their standard parameters and uncertainties on those parameters (Figs 1, 3). The models are different formulations of the same fireball phenomenology.

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Figure 1 | Comparison of results to predictions based on observed γ-ray spectra. The summed flux predictions normalized to γ-ray spectra are shown as a function of neutrino energy (E) in dashed lines, with the dark grey dashed line labelled 'IC40 Guetta et al.' showing the flux prediction for the full two-year dataset. The cosmic ray normalized Waxman-Bahcall flux is also shown for reference as the pale grey dashed line. 90% confidence upper limits on these spectra are shown as solid lines, with the grey line labelled 'IC40 limit' showing the previous IceCube result and the black 'IC40+IC59 Combined' line showing the result from the full dataset (this work). The predicted neutrino flux, when normalized to the γ-rays, is proportional to the ratio of energy in protons to that in electrons, which are presumed responsible for the γ-ray emission (E/p, here the standard 10). The flux shown is slightly modified from the original calculation. Φ(vert) is the average neutrino flux at Earth, obtained by scaling the summed predictions from the bursts in our sample (F, right vertical axis) by the global GRB rate (here 667 bursts yr⁻¹, ref. 7). The first break in the neutrino spectrum is related to the break in the photon spectrum measured by the satellites, and the threshold for photo-pion production, whereas the second break corresponds to the onset of synchrotron losses of muons and pions. Not all of the parameters used in the neutrino spectrum calculation are measurable from every burst. In such cases, benchmark values were used for the unmeasured parameters. Data shown here were taken from the result of the model-dependent analysis.

Figure 2 | Upper limits on E^{-2} power-law muon neutrino fluxes. Limits were calculated using the Feldman-Cousins method from the results of the model-independent analysis. The left-hand γ-axis shows the total number of expected νμ events, while the right-hand γ-axis (Fν) is the same as in Fig. 1. A time window of ∆t implies observed events arriving between t seconds before the burst and t afterward. The variation of the upper limit (solid line labelled '90% Upper limit') with ∆t reflects statistical fluctuations in the observed background rate, as well as the presence of individual events of varying quality. The dashed line labelled '90% Sensitivity' shows the upper limit that would have been obtained with exactly the mean expected background. The event at 30 s (event 1) is consistent with background and believed to be a cosmic-ray air shower.

Figure 3 | Compatibility of some neutrino flux predictions based on cosmic ray production in GRBs with observations. The cross-hatched area shows the 90% confidence allowed values of the neutrino flux (vertical axes, as in Fig. 1) versus the neutrino break energy (E_b) in comparison to model predictions with estimated uncertainties (points); the solid line labelled 'IC50+59 Allowed 95% CL' shows the upper bound of the 95% confidence allowed region. Data were taken from the model-independent analysis from the time window corresponding to the median duration of the GRBs in our catalogue (|∆t| = 28 s). Spectra are represented here as broken power laws (Φν(E) = E^{-1.6}b, E < E_b E^{-2}, E > E_b) with a break energy E_b corresponding to the A resonance for p-γ interactions in the frame of the shock. The muon flux in IceCube is dominated by neutrinos with energies around the first break (E_b). As such, the upper break, due to synchrotron losses of νμ, has been neglected here, as its presence or absence does not contribute significantly to the muon flux and thus does not have a significant effect on the presented limits. E_b is related to the bulk Lorentz factor Λ (E_b ∝ Λ^2); all of the models assume Λ = 300. The value of Λ corresponding to 10^7 GeV is >1,000 for all models. Vertical axes are related to the accelerated proton flux by the model-dependent constant of proportionality f_p. For models assuming a neutron-decay origin of cosmic rays (ref. 8 and ref. 10), f_p is independent of Λ; for others (ref. 8), f_p ∝ Λ^{0.5}. Error bars on model predictions are approximate and were taken either from the original papers, where included, or from the best-available source in the literature otherwise. The errors are due to uncertainties in f_p and in fits to the cosmic-ray spectrum. Waxman-Bahcall (circle) and Rachen (box) fluxes were calculated using a cosmic-ray density of (1.5–3) × 10^{44} erg Mpc⁻³ yr⁻¹, with 3 × 10^{44} the central value. The Ahlers model is shown with a cross. CL, confidence level.
Figure 4 | Constraints on fireball parameters. The shaded region, based on the result of the model dependent analysis, shows the values of GRB energy in protons and the average fireball bulk Lorentz factor for modelled fireball, allowed by this result at the 90% confidence level. The dotted line indicates the values of the parameters to which the completed IceCube detector (IC86) is expected to be sensitive after 3 years of data. The standard values considered are shown as dashed-dotted and dashed lines and are excluded by this analysis. Note that the quantities shown here are model-dependent.

production arguments, but the upper limit is less clear. Although it is possible that \( \Gamma \) may take values of up to 1,000 in some unusual bursts, the average value is probably lower (usually assumed to be around 300) and the non-thermal \( \gamma \)-ray spectra from the bursts set a weak constraint that \( \Gamma \lesssim 2,000 \) (ref. 18). For all considered models, with uniform fixed proton content, very high average values of \( \Gamma \) are required to be compatible with our limits (Figs 3, 4).

In the case of models where cosmic rays escape from the GRB fireball as neutrons, the neutrons and neutrinos are created in the same \( p-\gamma \) interactions, directly relating the cosmic-ray and neutrino fluxes and removing many uncertainties in the calculation. In these models, \( \Gamma \) also sets the threshold energy for production of cosmic rays. The requirement that the extragalactic cosmic rays be produced in GRBs therefore does set a strong upper limit on \( \Gamma \): increasing it beyond \( \Gamma \approx 1,000 \) causes the proton flux from GRBs to disagree with the measured cosmic-ray flux above \( 4 \times 10^{18} \) eV, where extragalactic cosmic rays are believed to be dominant. Limits on \( \Gamma \) in neutron-origin models from this analysis (\( \Gamma \geq 200 \), Fig. 3) are very close to this point, and as a result all such models—in which all extragalactic cosmic rays are emitted from GRBs as neutrons—are now largely ruled out.

Although the precision constraints are model-dependent, the general conclusion is the same for all the versions of fireball phenomenology we have considered here: either the proton density in GRB fireballs is substantially below the level required to explain the highest-energy cosmic rays or the physics in GRB shocks is significantly different from that included in current models. In either case, our current theories of cosmic-ray and neutrino production in GRBs will need to be revisited.

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1. Waxman, E. Cosmological gamma-ray bursts and the highest energy cosmic rays. Phys. Rev. Lett. 75, 386–389 (1995).
2. Vietri, M. The acceleration of ultra-high-energy cosmic rays in gamma-ray bursts. Astrophys. J. 453, 883–889 (1995).
3. Milgrom, M. & Usov, V. Possible association of ultra-high-energy cosmic-ray events with strong gamma-ray bursts. Astrophys. J. 449, L37 (1995).
4. Waxman, E. & Bahcall, J. High energy neutrinos from cosmological gamma-ray burst fireballs. Phys. Rev. Lett. 78, 2292–2295 (1997).
5. Avrorin, A. V. et al. Search for neutrinos from gamma-ray bursts with the Baikal neutrino telescope. Astrophys. J. 710, 346–359 (2010).
6. Abbasi, R. et al. Search for muon neutrinos from gamma-ray bursts with the IceCube neutrino telescope. Astrophys. J. 1141101 (2011).
7. Rachen, J. P. & Mészáros, P. in Fourth Huntsville Gamma-Ray Burst Symposium (eds Meegan, C. A., Preece, R. D. & Akhutin, T. M.) 776–790 (American Institute of Physics Conference Proceedings Vol. 428, 1998).
8. Guetta, D., Hooper, D., Alvarez-Muñiz, J., Halzen, F. & Reuveni, E. Neutrinos from individual gamma-ray bursts in the BATSE catalog. Astropart. Phys. 20, 429–455 (2004).
9. Ahlers, M., Gonzalez-Garcia, M. C. & Halzen, F. GRBs on probation: testing the UHE CR paradigm with IceCube. Astropart. Phys. 35, 87–94 (2011).
10. Becker, J. K. High-energy neutrinos in the context of multimessenger astrophysics. Phys. Rep. 456, 173–246 (2008).
11. Abbasi, R. et al. The IceCube data acquisition system: signal capture, digitization, and timestamping. Nucl._instrum. Methods Phys. Res. A 601, 294–316 (2009).
12. Ahrens, J. et al. Muon track reconstruction and data selection techniques in AMANDA. Nucl. instrum. Methods Phys. Res. A 524, 169–194 (2000).
13. CNO: The Gamma-Coordinates Network. http://goncsfc.navy.mil/.
14. Guetta, D., Spada, M. & Waxman, E. On the neutrino flux from gamma-ray bursts. Astrophys. J. 559, 101–109 (2001).
15. Baerwald, P., Hüümer, S. & Winter, W. Systematics in aggregated neutrino fluxes and flavor ratios from gamma-ray bursts. Astropart. Phys. 35, 508–529 (2012).
16. Hümmer, S., Baerwald, P. & Winter, W. Neutrino emission from gamma-ray burst fireballs, revised. Preprint at http://arXiv.org/abs/1112.1076 (2011).
17. Mészáros, P. Gamma-ray bursts. Rep. Prog. Phys. 69, 2259–2321 (2006).
18. Becker, J. K., Statnikov, M., Halzen, F. & Rhode, W. Coincident GRB neutrino flux predictions: implications for experimental UHE neutrino physics. Astropart. Phys. 25, 118–128 (2006).
19. Waxman, E. Astrophysical sources of high energy neutrinos. Nucl. Phys. B Proc. Suppl. 118, 353–362 (2003).
20. Federman, G. & Higson, P. Unified approach to the classical statistical analysis of small signals. Phys. Rev. D 57, 3873–3889 (1998).

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