29th International Cosmic Ray Conference Pune (2005) **9**, 271–274

Using RICE Data and GZK Neutrino Flux Models to Bound Low Scale Gravity

I. Kravchenko[a], C. Cooley[b], D. Seckel[c],J. Adams,[d], S. Churchwell[d], P. Harris[d], S. Seunarine[d], P. Wahrlich, [d], A. Bean[e], D. Besson[e], S. Graham[e], S. Holt[e], S. Hussain[e], D. Marfatia[e], D. McKay[e], J. Meyers[e], J. Ralston[e], R.Schiel[e], H. Swift[e], J. Ledford[f] and K. Ratzlaff[f]

(a) M.I.T Lab. for Nuclear Science, Cambridge, MA 02139
(b) Whitman College Dept. of Physics, Walla Walla , WA 99362
(c) Bartol Research Institute, U. of Delaware, Newark, DE 19716
(d) Department of Physics and Astronomy, Private Bag 4800, U. of Canterbury, Christchurch, New Zealand
(e) U. Kansas Dept. of Physics and Astronomy, Lawrence KS 66045-2151
(f) U. Kansas Instrumentation Design Laboratory, Lawrence KS 66045-2151
Presenter: I. Kravchenko (ikrav@cdfsga.fnal.gov), usa-mckay-D-abs1-he23-poster

Abstract

We report calculations in low-scale gravity models of expected numbers of events in the updated analysis of Radio Ice Cherenkov Experiment (RICE) data, collected from the beginning of 2000 to the end of 2004. RICE found no neutrino candidates in the 2000 - 2004 data analysis, which allows us to place bounds on low scale gravity parameters for a range of cosmogenic neutrino flux models. Requiring that the black hole formation threshold satisfy $M_{BH} \geq M_D$, the extra-dimensional Planck scale, we find 95% C.L.bounds on M_D for M_{BH}/M_D in the range 1< M_{BH}/M_D < 10, for six extra dimensions and a wide range of flux models.

1. Introduction and background

In this paper we present bounds on new physics, specifically low scale gravity models[1], that follow from proposed models of cosmogenic neutrino fluxes[2, 3, 4, 5] and the absence of UHE neutrino events above 10^2 PeV in the Radio Ice Cherenkov Experiment (RICE) data from 2000 through 2004 [6]. Before proceeding to a description of the calculation, the results and the summary and conclusions, we sketch the essential concept of the RICE detection system and the features of low scale gravity that lead to prediction of event rates in RICE exceeding those expected from neutrino interactions in the SM.

The RICE experiment: The RICE detector concept rests on several key features of UHE neutrino induced showers, the radio wavelength emission from these showers and the transmission of radio wavelengths in cold, pure ice. The showers in dense media like ice, are quite compact, moving at speeds faster than light in the medium and smaller in transverse size than GHz frequency wavelengths. The showers develop a net excess charge at shower maximum that is about 10^6 electrons at a PeV and rises linearly with energy. This net charge emits *coherent* Cherenkov radiation at frequencies at a GHz and below, radiation which has an attenuation length of a kilometer or more in Antarctic ice, as confirmed directly by *in situ* measurements [9]. An individual radio antenna can be sensitive to neutrino induced showers over a km^3 of ice at the highest energies; even a modest, pilot array has an effective volume, V_{eff}, of many cubic kilometers. Details of the recent RICE analysis can be found in [6], while more details of the full experiment are given in [7],[8].

Low scale gravity and UHE cosmic ray neutrinos: Low scale gravity (LSG) [1] predicts gravity mediated, enhanced cross sections, including high rates of TeV-scale black hole production in high energy particle reactions. It is argued that after formation black holes evaporate primarily to observable, standard model particles, and failed searches for signatures low scale gravity - missing energy ascribable to graviton emission or thermal decay of black holes in accelerator experiments, or enhanced event rates in ultrahigh energy neutrino telescopes

- have resulted in bounds on the scale of gravity and number of extra dimensions, in the case of large extra dimension models. The larger numbers of dimensions, d = 5, 6 and 7, are still relatively unconstrained, and we choose d = 6 for this study. The results for d = 5 and d = 7 differ little from those presented here. The ”new physics” signal in neutrino telescopes is primarily an enhanced event rate compared to the anticipated SM rate for the same flux. In the RICE detector, this means an enhanced rate of neutrino induced showers. Graviton exchange produces hadronic showers in gravity induced, ”neutral-current”- like events, while black hole formation and decay produces largely hadronic shower events.

Summary of LSG cross sections and rate predictions: We recap here the essential components of our calculation of the number of events expected in RICE data from SM, black hole, and graviton-mediated interactions. For impact parameters less than r_S, we first use the black disk, black hole cross section formula $\hat{\sigma}_{\rm BH} \approx \pi r_S^2,$. In our rate calculations below, we also include a model for the impact parameter (inelasticity) dependence for comparison. In Eq. (1), r_S is the 4+d dimensional Schwartzschild radius of a black hole of mass M_{BH}. For the case d = 6, which we use throughout, we have $r_S = 2.44 \frac{1}{M_D} \left[\frac{M_{\rm BH}}{M_D}\right]^{\frac{1}{7}}$ Here M_D is the 4+d dimensional Planck mass scale of extra-dimensional physics, typically of order TeV. $\hat{\sigma}_{\rm BH}$ is a parton level cross section, and the effective black hole mass is $M_{BH} = \sqrt{\hat{s}}$, with $\hat{s} = xs$, and x is the momentum fraction of the struck parton. The corresponding cross section is given by $\sigma_{BH}(s, x, Q) = \hat{\sigma}_{BH}(xs) f(x, Q)$, where $f(x, Q)$ is the sum over parton distribution functions. The choice of Q is not unique, but the results are not particularly sensitive to the value used for Q. We treat the graviton exchange in the higher dimension, low scale gravity picture in the eikonal approximation [10], with a cutoff on the tower of Kaluza-Klein contributions to the propagator equal to M_D. For more than 3 spatial dimensions, an impact parameter scale b_c enters the problem, and the dominant contribution to the eikonal amplitude when $\sqrt{\hat{s}} \gg M_D$ comes from momentum transfer $q = \sqrt{-(p-p')^2}$ in the range $1/r_S > q > 1/b_c$, where the stationary phase evaluation of the amplitude is a good approximation. The four momenta p and p' refer to the incident and scattered neutrinos respectively. The eikonal amplitude can be written in this approximation:

$$|\mathcal{M}_d| = B_d (b_c M_D)^{d+2} \left[b_c q\right]^{-\frac{d+2}{d+1}} \quad ,$$

where, for d = 6, B_d = 0.0389, and $b_c = 2.06 \frac{1}{M_D} \left(\frac{s}{M_D^2}\right)^{\frac{1}{d}}$. The elastic parton level cross section then reads, $\sigma_{EK}(s, x, q) = f(x, q) |\mathcal{M}_d|^2 / (16 \pi x s)$, which enters into the rate calculations described below.

At this point we can write the shower production rates for the eikonal and direct black hole production cases, specifying the restrictions on the range of integrations from impact parameter and threshold considerations.

Shower rates for BH, without black hole impact parameter effects, or inelasticity, can be expressed as follows:

$$R^{BH}_{shower} \cong \rho N_A \sum_i \int\limits_{E_{th}}^{E_{\nu i}\,\max} dE_{\nu_i} \frac{dF(E_{\nu_i})}{dE_{\nu_i}} V_{eff}(E_{\nu_i}) \times \int_{x_{min}}^{1} dx \hat{\sigma}_{BH}(s, x, Q), \tag{1}$$

where, $x_{\rm min} = M_{BH0}^2 / s$ or $1/r_s^2 s$, whichever is larger; the sum over index i accounts for different flavors; here $s = 2 M_N E_{\nu_i}$ and Q is chosen to be xs. Choosing $Q = \frac{1}{r_s}$ makes insignificant difference. E_{th} is the threshold for experimental detection of showers. To include an estimate of the impact parameter effects, we follow the analysis of [11] and [12]. In [11], the mass-energy, $M_{AH}(z = b/b_{max})$, contained within an apparent horizon that depends on impact parameter, b, serves as the effective black hole mass. The prescription of [12] weights each impact parameter by $d(\pi b^2)/\pi b_{\rm max}^2$, introduces $\rm x_{min} = (M_{BH}^{\rm min})^2 / M_{A.H.}^2(z)$, and integrates over b from 0 to b_{max}.

For the eikonal scattering case, the rate expression includes an integral over the inelasticity y, an x-integration restricted to $M_D^2/ys < x < 1/r_s^2 ys$, and the eikonal cross section in place of the BH cross section.

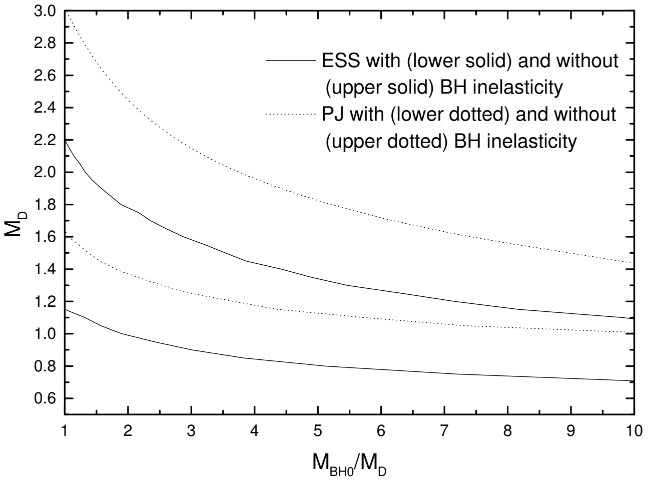

Figure 1. Lower bounds on M_D as a function of the ratio of the minimum BH formation threshold, M_{BH}, to M_D. The upper curve for each flux model is the lower bound when the naive, black disk model is used for the BH cross section. The lower curve is the lower bound when the estimate of impact parameter effects is included. ESS, KKSS and PJ refer to Refs. [2], [3] and [4]

2. Results, discussion and outlook

In Fig. 1 we show the minimum value of the scale of gravity allowed by RICE data at 95% C.L. The lower bound on M_D is plotted against the ratio of a minimum invariant mass required for black hole formation to the scale of gravity. In setting the limit curves, the SM, LSG unitarized graviton exchange, and the LSG black hole production cross sections are all included in determining events rates and, consequently, the bound. The top curve represents the minimum M_D when the simple "black disk" model for the black hole formation cross section is used, while the bottom curve indicates the lower limit when impact parameter dependence of the apparent horizon is included as estimated in [11] and implemented by [12]. The ESS flux model, the most conservative among those we consider here, is used for this display. The PJ cosmogenic flux model, used for illustration in references [12], is larger by roughly a factor 3 and gives us a bound larger by a factor of about 1.4 than those shown in Fig. 1. The KKSS model is essentially at the RICE standard model 95% C.L.bound[6], and the bounds are a factor of about 5 times the ESS bounds in Fig. 1. For several selected cases, Table 1 shows the break-down of the values of bounds on M_D coming from EK , BH with and without inelasticity, and then the bound including everything. The SM contribution is included in every entry. Within the range of cosmogenic flux models we consider, Fig. 1 and Table reveal that at 95% C. L., RICE and the ESS flux model [2] rules out a LSG model for which the naive $\sigma_{BH} = \pi \times r_S^2$ cross section is assumed, where $M_{BH} = 3M_D$, and where $M_D < 1.55$ TeV. This can be regarded as a least lower bound on models with the naive "black disk" cross section for the black hole formation within our analysis assumptions. The greatest lower bound corresponds to that obtained with the largest KKSS flux model, and that value is greater than about 10 TeV. The KKSS flux model [3] is on the borderline of our 95% C.L. constraint using the SM cross section[6], so the the corresponding bound on the LSG scale is large, but imprecise. The range of values $M_D >$ 5-10 TeV in Table 1 is indicative.

If the estimate of the effects of non-zero impact parameter are included in the manner proposed in [11], and some of the collision energy is lost to the BH formation process, then the BH formation cross sections decrease and the event rates and corresponding bounds on the LSG scale weaken. The nominal effects on the least lower

Table 1. Experimental lower bounds on LSG scale M_D, based on 2000-2004 RICE data (0 events, 0 background). Here 'ALL' is the combined bound due to EK and BH; these bounds are due to all flavors. The pairs of numbers under columns BHD and 'ALL' are the bounds without and with black hole inelasticity, respectively. The bounds here include SM interactions. The numbers are in TeV. We fix number of extra dimensions d to 6.

Flux	$M_{BH_0} = M_D$			$M_{BH_0} = 3M_D$	
	EK	BH	ALL	BH	ALL
ESS	0.6	$2.18, 1.1$	$2.2, 1.15$	$1.55, 0.8$	$1.57, 0.9$
$KKSS$	4.85	$11, 6.0$	$11, 6.7$	$7.5, 4.1$	$7.9, 5.5$
PJ	0.9	$3.0, 1.52$	$3.0, 1.63$	$2.1, 1.1$	$2.15, 1.25$

bound, tied to the flux model [2], and greatest lower bound, tied to KKSS[3] are the reductions to 0.9 TeV and 5.5, respectively, seen in Table 1. Given the lack of precision in these considerations, we summarize the bounds on M_D as 1 TeV $<$ M_D $<$10 TeV.

Continued data taking through the next several years should translate into a factor two or so improvement on flux bounds and roughly 25$\%$ strengthening of the bounds on the LSG Planck mass. A detector development and array optimization program for a combined radio and acoustic detector in conjunction with ICECUBE is ongoing. With these designs for improved instrumentation and an expanded array, with corresponding sensitivity to fluxes and new physics signals, future gain in sensitivity by more than an order of magnitude is anticipated.

References

[1] N. Arkani-Hamed, S. Dimopoulos and G. Dvali, Phys.Lett. B **429** (1998) 263; I. Antoniadis, N. Arkani-Hamed, S. Dimopoulos and G. Dvali, Phys.Lett. B **463** (1998) 257.

[2] R. Engel, D. Seckel, and I. Stanev, Phys. Rev. D **64**, 093010 (2001).

[3] O. E. Kalashev, V. A. Kuzmin, D. V. Semikoz, and G. Sigl, Phys. Rev. D **66**, 063004 (2002).

[4] R. Protheroe and P. Johnson, astro-ph/9506119, Astropart. Phys. **4**, 253 (1996).

[5] Z. Fodor, S. D. Katz, A. Ringwald, and H. Tu, hep-ph/0309171, JCAP 0311, 115 (2003).

[6] RICE collaboration, I. Kravchenko *et. al* (These proceedings and in preparation).

[7] RICE Collaboration, I. Kravchenko *et al.*, Astroparticle Physics **19**, 15 (2003); Astroparticle Physics, **20**, 195 (2003).

[8] The RICE collaboration, I. Kravchenko *et. al*, in proceedings of 28th ICRC, Tokyo, 2003 (Universal Academy Press, Tokyo, 2003).

[9] Kravchenko, I, *et al.* "*In situ* measurements of the index of refraction of the South Polar firn with the RICE detector", *J. Glaciol.* in press.

[10] R. Emparan, Phys. Rev. D **64**, 0204025 (2001); S. Hussain and D. McKay, Phys. Rev. D **69**, 085004 (2004).

[11] H. Yoshino and Y. Nambu, Phys. Rev. D **67**, 024009 (2002).

[12] L. anchordoqui, J. Feng, H. Goldberg and A. Shapere, Phys. Rev. D textbf68, 104025 (2003).