Prospects for radio detection of extremely high energy cosmic rays and neutrinos in the Moon

Jaime Alvarez-Muñiz* and Enrique Zas†

*Bartol Research Institute, University of Delaware, Newark, DE 19711
†Departamento de Física de Partículas, Universidade de Santiago de Compostela, E-15706, Santiago de Compostela, Spain

Abstract. We explore the feasibility of using the Moon as a detector of extremely high energy ($> 10^{19}$ eV) cosmic rays and neutrinos. The idea is to use the existing radiotelescopes on Earth to look for short pulses of Cherenkov radiation in the GHz range emitted by showers induced just below the surface of the Moon when cosmic rays or neutrinos strike it. We estimate the energy threshold of the technique and the effective aperture and volume of the Moon for this detection. We apply our calculation to obtain the expected event rates from the observed cosmic ray flux and several representative theoretical neutrino fluxes.

INTRODUCTION

The observation of atmospheric showers with total energy above the so-called GZK cutoff at energies above $\sim 5 \times 10^{19}$ eV, is one of the most puzzling mysteries of the emerging field of astroparticle physics [1]. The nature of the primaries is still unknown as well as their origin and the mechanisms involved in their acceleration to such energies. The puzzle is even more intriguing because if the primaries are protons, photons or nuclei they should be produced within distances of a few tens of megaparsecs from us, otherwise their interactions with the 2.7 K photons constituting the Cosmic Microwave Background (CMB) as well as with the infrared and radiobackgrounds, should greatly reduce their energy. Since no effective sources capable of accelerating them have been identified within that distance, their very presence is contrary to the expectations. Neutrinos may play a fundamental role in solving this puzzle. They may be produced in interactions of the primary cosmic rays with the matter and radiation in the source or in the matter and radiation they find along their paths to Earth. The so-called GZK neutrinos produced in interactions of cosmic rays with the CMB are almost guaranteed, since both the projectile and the target are known to exist [2,3]. Sources in which ultra high energy neutrinos may be produced include AGN's and GRB's [4] where accelerated particles interact with matter or radiation. Alternative sources are the annihilation of topological defects which can be produced in phase transitions in the early universe where extremely high densities of energy are trapped [5].

Some present and future detectors of ultra high energy cosmic rays [1,6–8] and neutrinos [4,9,10] will soon remedy the lack of statistics [11]. The small observed (predicted) fluxes of ultra high energy cosmic rays (neutrinos) call for huge effective volumes (measured in km^3). Several detection methods and techniques are being employed and/or studied to achieve the required volumes, some of them have been discussed in this workshop [12]. Among them the radio technique is one of the most promising alternatives for neutrino and possibly cosmic ray detection at ultra high energies (10^{15} eV and above). The technique aims at detecting *coherent* Cherenkov radiation in the MHz-GHz range from the excess of electrons in showers initiated by photons or electrons. Several detectors are being planned [12] or they are in the early stages of construction [13]. Due to its excellent radio frequency wave propagation properties, Antarctic ice is being considered as a medium where antennas are being placed to monitor the potential radio signals. Other media such as salt [14] and sand are also being studied. As an interesting alternative, in 1989 Zheleznykh et al. [15] proposed to detect showers initiated by cosmic ray and neutrinos by measuring coherent Cherenkov radiation emitted just below the surface of the Moon when high energy cosmic rays or neutrinos strike it. Two groups have looked for those signals using existing radiotelescopes on Earth with no positive detection during the time they have pointed the instruments to the Moon [16,17].

Here we investigate the feasibility of detecting extremely high energy particles interacting in the Moon. We discuss the characteristics of the radio signals and we stress how they influence the aperture of the Moon as a high energy particle detector. We calculate the energy threshold for the technique as a function of the detector parameters and the signal's main features. Using several representative neutrino fluxes, we estimate the expected event rates and we briefly discuss where, on the surface of the Moon, should the radiotelescopes be pointed at to be able to detect them. We also discuss cosmic ray detection. This work updates previous estimates in which some approximations to extremely high energy shower development in the lunar rock as well as to the associated radiosignals were used [18]. We also take into account the transmissivity of the signals through the Moon's surface and some other geometrical issues which were not fully considered in our previous estimates.

RADIOPULSES IN THE MOON

Neutrino interactions produce different types of showers depending on the neutrino flavor and on whether the interaction is mediated by a $W^{\pm}$ or a Z boson. In deep inelastic scattering (DIS) charged current (CC) interactions of electron neutrinos (ν_e), the electron produced in the lepton vertex initiates an electromagnetic shower of energy $(1-y)E_\nu$, where E_ν is the neutrino energy in the laboratory frame and y is the fraction of energy transferred to the struck nucleon in the hadronic vertex. The debris of the nucleon initiate a hadronic shower which is superimposed to the electromagnetic one producing a "mixed shower". Hadronic showers are also initiated in both charged and neutral current (NC) DIS neutrino interactions by the hadrons created in the fragmentation of the nuclear debris. At shower energies above $E_{\rm LPM} \sim 4 \times 10^{14}$ eV (400 TeV) in the lunar regolith, electromagnetic showers are affected by the LPM effect [19]. When the energy of a photon or electron in the shower is above $E_{\rm LPM}$ the interaction distance becomes comparable to the inter-atomic spacing and collective atomic and molecular effects affect the static electric field responsible for the interaction. The result is a reduction in both total cross sections with lab energy (E) which drop like $E^{-0.5}$ above $\sim E_{LPM}$. As a result PeV - EeV photon or electron induced showers are considerably larger than at TeV energies [20]. In hadronic showers this effect is mitigated because the main source of photons is the decay of π^0's which at energies above $E_{\pi^0} = 7 \times 10^{15}$ eV (7 PeV) is suppressed due to the dominance of π^0 interaction [21].

A helpful way of getting insight into the pattern of the electric field emitted by the excess of electrons in the shower, is to think of a shower as a slit illuminated by radio-waves [22]. The diffraction pattern can be obtained as the Fourier transform of the slit, however due to the nature of the Cherenkov radiation the emission has a central peak with its maximum at the Cherenkov angle instead of in the direction perpendicular to the slit. The radiation is coherent when the wavelength is larger than the physical dimensions of the shower. In this situation the radiated electric field becomes proportional to the excess charge and the power in radiowaves scales with the square of the shower energy. This effect was predicted in the 1960's by Askary'an [23] and has been observed recently at SLAC in experiments where an intense beam of GeV photons generates a shower inside a sand target [24]. Given this interpretation it is easy to understand that the LPM effect is going to reduce the angular width of the Cherenkov peak ($\Delta\theta$) in electromagnetic showers as shower energy increases. Following the same reasoning, the diffraction pattern from hadronic showers is expected to be less affected by the LPM, exhibiting a mild decrease of $\Delta\theta$ with energy [21].

The spectrum of the electric field also increases linearly with frequency up to a maximum frequency which is essentially determined by the lateral structure of the shower at the Cherenkov angle, the wider the shower the smaller the corresponding maximum frequency. At angles away from the Cherenkov angle, the maximum frequency depends only on the longitudinal dimension of the shower. We have performed simulations of electromagnetic showers in the lunar regolith assumed homogeneous (density $\rho \simeq 1.6$ g cm^{-3}). We have adapted the ZHS code [25] originally conceived for simulations in ice, changing the relevant parameters such as density, radiation length, atomic number and refraction index. The frequency spectrum as well as the angular distribution of the pulses emitted by a 100 TeV electromagnetic shower in the Moon are shown in Fig.1. The results of the simulations are in very good agreement with a simple scaling of the simulations from ice to the Moon [18]. With this in mind we have obtained the electric field from electromagnetic showers at the highest energies, by scaling the spectral features in ice. The same scaling has been applied to estimate the radiopulses from hadronic showers. The absolute value of the electric field has been normalized according to the amount of electromagnetic energy present in the hadronic shower, and the width of the Cherenkov peak, which is inversely proportional to the longitudinal dimension of the shower, is scaled with the radiation length and the density of the medium [18]. Simulation work is in progress in this direction and will be published elsewhere. For more details see references [20,21].

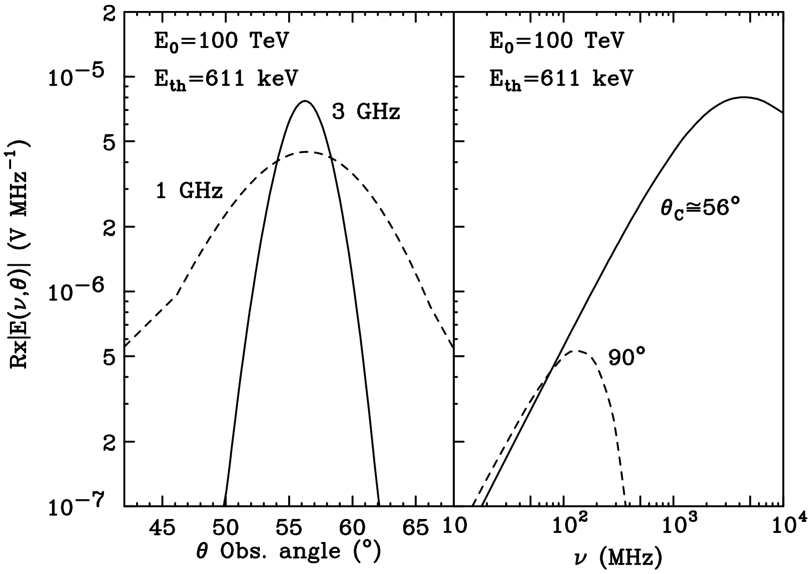

FIGURE 1. Left panel: Results of simulations of the angular behavior of the electric field emitted by a 100 TeV electromagnetic shower in the lunar regolith. θ is the observation angle with respect to the shower axis. Two frequencies are shown. Right panel: Frequency spectrum of the electric field at two observation angles.

APERTURE OF THE MOON FOR NEUTRINO AND COSMIC RAY DETECTION: ENERGY THRESHOLD

One important parameter for assessing the possibilities of using the Moon as a high energy particle detector is the energy threshold for shower observation by radiotelescopes on Earth. This can be estimated comparing the radio signal emitted by an electromagnetic shower at the Cherenkov peak and the noise expected by other processes in the radiotelescope. Here we only take into account thermal noise for which we use two representative values, namely 1σ and 6σ of the flux density given by the standard expression for a radio antenna:

$$F_{\rm Noise} = \frac{2k_{\rm B}T_{\rm sys}}{\sqrt{\Delta{\rm t}\Delta\nu}A_{\rm eff}}. \tag{1}$$

Here k_B is Boltzmann's constant, T_{sys} is the noise temperature of the radio detection system, Δt and $\Delta\nu$ are respectively the duration of the pulse and the bandwidth of the detection system around a central frequency ν_C. A_{eff} is the effective area of the antenna. We have estimated the energy threshold for the NASA/JPL Goldstone Deep Space Station 14 (70 m diameter dish) radio telescope [26] with which the measurements in [17] were performed. The 1σ thermal noise level for this system is $\sim$ 400 Jy [1] and the 6σ is 2,400 Jy. The flux density on Earth emitted by an electromagnetic shower at the Cherenkov peak is obtained integrating the frequency spectrum of the electric field $\mathrm{R}\mathbf{E}(\nu, \mathrm{R}, \theta_{\mathbf{Cher}})$, where R is the distance to the shower, around ν_C:

$$F_{\rm Signal} = \int_{\nu_C+\frac{\Delta\nu}{2}}^{\nu_C-\frac{\Delta\nu}{2}} |\mathrm{R}\mathbf{E}(\nu, \mathrm{R}, \theta_{\mathbf{Cher}})|^2 \, d\nu \; / \; (4\pi \mathrm{R}^2_{\rm Earth\to Moon}). \tag{2}$$

$\mathrm{R}_{\rm Earth\to Moon}$ is the distance from Earth to the Moon. The result of this calculation for electromagnetic showers is shown in Fig.2. Reading from the plot one can estimate the energy threshold of a electromagnetic shower to be between $E_{\rm th} \sim 10^{19} - 10^{20}$ eV depending on the noise level, the central frequency and assuming a bandwidth of $\sim 0.1\ \nu_C$. To translate the electromagnetic shower energy threshold

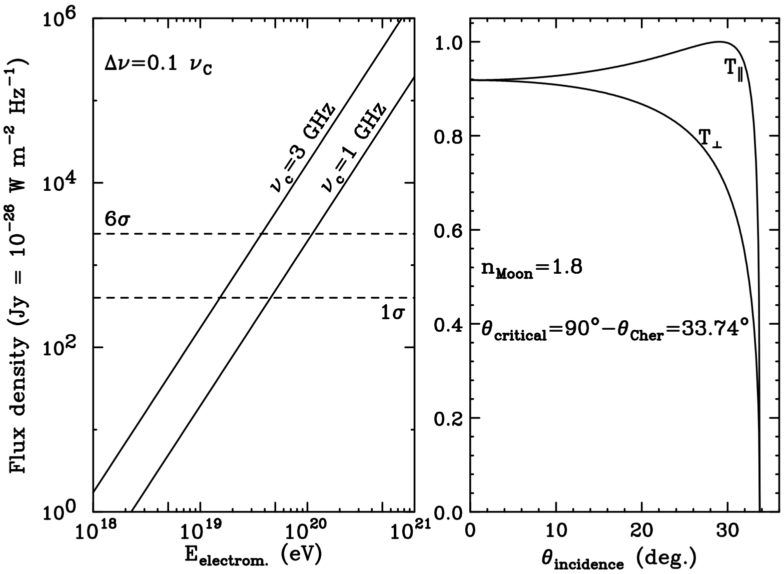

FIGURE 2. Left panel: Flux density at Earth emitted by an electromagnetic shower of energy $E_{\rm electrom.}$ for two central frequencies and a bandwidth $\Delta\nu = 0.1\nu_C$. Also shown is the flux density of the thermal noise in NASA/JPL Goldstone DSS 14 radiotelescope. Right panel: Transmissivity ($\mathrm{Power_{transmitted}/Power_{incident}}$) of radio waves at the Moon-vacuum interface as a function of the incidence angle with respect to the perpendicular to the local surface of the Moon.

into a neutrino or cosmic ray energy threshold, one has to keep in mind that at

---

[1] 1 Jy = 10^{-26} W m^{-2} Hz^{-1}

extremely high energy the electromagnetic energy content of a hadronic shower in the lunar regolith is $\sim 90\%$ of the total shower energy, slowly increasing with it [21] and the typical value of y is ~ 0.2 [27]. This implies that the energy threshold for detecting a NC neutrino DIS interaction is roughly $E_\nu \sim 5E_{\rm th}$ whereas it is $\sim E_{\rm th}$ for detection of CR or for a CC ν_e interaction.

Aperture

We have studied in detail the geometry of the problem in order to calculate the aperture (effective area x solid angle) of the Moon for neutrino as well as cosmic ray detection.

For a cosmic ray or a neutrino to be detected it has to interact producing a shower within a distance to the surface of the Moon equal to the typical absorption length of radiowaves inside the lunar regolith: $\lambda_{\rm abs}^{\rm radio} \sim 15\,{\rm m}(1\,{\rm GHz}/\nu)$. The emitted radiowave then reaches the surface of the Moon without significant attenuation and has to point to the Earth after refraction in the Moon-vacuum interface. We restrict ourselves to radio emission from the directions between the Cherenkov angle and $\theta_C \pm \Delta\theta$, where most of the power is concentrated. These two considerations allowed us to obtain the potentially detectable incident neutrino and cosmic ray directions. Then we disregarded those directions for which either the cosmic rays or neutrinos are absorbed inside the Moon before reaching its surface[2]. It requires a little bit of thinking and the aid of Fig.3 to realize that this limits the potential interaction points on the surface of the Moon to a fairly narrow rim for cosmic rays and to a wider rim for neutrinos. It also restricts the observed cosmic rays to those hitting the Moon with their tracks almost parallel to its surface. We finally eliminated those directions (and energies) for which the signal, although being "geometrically able" to reach Earth, is below the noise flux density. In this respect the transmissivity properties of the Moon-vaccumm interface play a fundamental role. For a shower propagating inside the Moon parallel to the local surface, the radiation emitted at the Cherenkov angle suffers total internal reflection since the Cherenkov angle is the complementary of the total internal reflection angle. However detection is still possible because, as we mentioned above, the radiation is emitted in a cone of width $\Delta\theta$ and the transmissivity of the interface increases to almost 1 just a few degrees off the total internal reflection angle as can be seen in Fig.2. Our results on the aperture are shown in Fig.4. It is interesting to notice that for hadronic showers once the energy threshold is reached, the aperture varies slowly with shower energy, the reason for this being that the effective solid angle is not restricted by an energy decrease of $\Delta\theta$ caused by the LPM effect. This is not the case for electromagnetic showers where the decrease of the aperture with energy is induced by a corresponding reduction in $\Delta\theta$ due to the LPM. The inner panel in Fig.4 represents the visible face of the Moon and gives an idea of the size of

[2] The interaction length ${\rm L_{int}}^\nu$ of a neutrino is smaller than the diameter of the Moon when $E_\nu > 10$ PeV

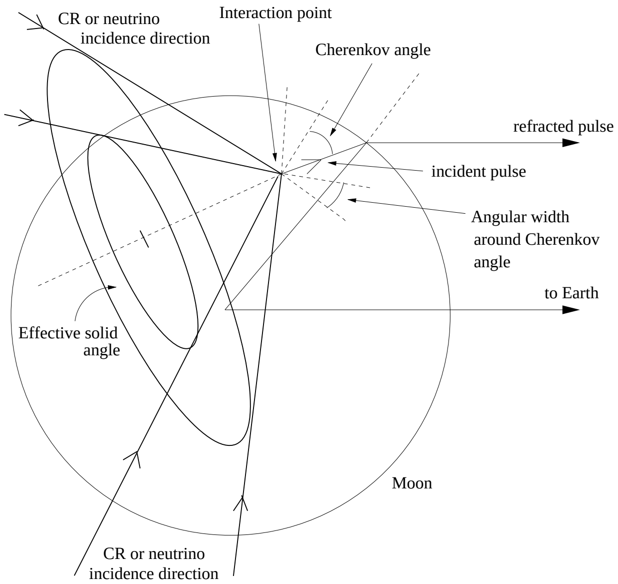

FIGURE 3. Main elements entering in the geometry of radio detection in the Moon. All the cosmic ray and neutrino directions entering in the depicted effective solid angle are "geometrically allowed", although many of them are disregarded due to absorption inside the Moon or threshold effects (see text).

the rim where cosmic ray and neutrino detection might be expected at 10^{21} eV. When combining the aperture with $\lambda_{\rm abs}^{\rm radio}$ acceptances in excess of 1000 km^3 sr at $E_\nu \sim 10^{20}$ eV might be achieved.

EVENT RATE ESTIMATES

Cosmic ray event rates are calculated in a straightforward manner by convoluting the experimentally observed flux and the aperture of the Moon. For neutrinos the convolution involves the theoretically expected neutrino flux, the neutrino cross section and the effective volume of the detector:

$$N_{\rm CR} = \int_{E_{\rm CR}} \frac{d\Phi_{\rm CR}}{dE_{\rm CR}}\, S_\Omega^{\rm CR}\, dE_{\rm CR} \quad ({\rm yr}^{-1}); \quad \text{for cosmic rays,} \tag{3}$$

$$N_\nu = \int_{E_\nu} \frac{d\Phi_\nu}{dE_\nu}\, S_\Omega^\nu\, \frac{\lambda_{\rm abs}^{\rm radio}}{{\rm L_{int}}^\nu} dE_\nu \quad ({\rm yr}^{-1}); \quad \text{for neutrinos,} \tag{4}$$

where $S_\Omega^{CR,\ \nu}$ is the aperture of the detector.

In Fig.5 we show the event rates for the conservative case where the noise level is equal to 6σ of the thermal noise. We have used some neutrino fluxes representative of the different current models and theoretical ideas. For the cosmic ray event rate, we have used a simple parameterization of the experimentally observed flux

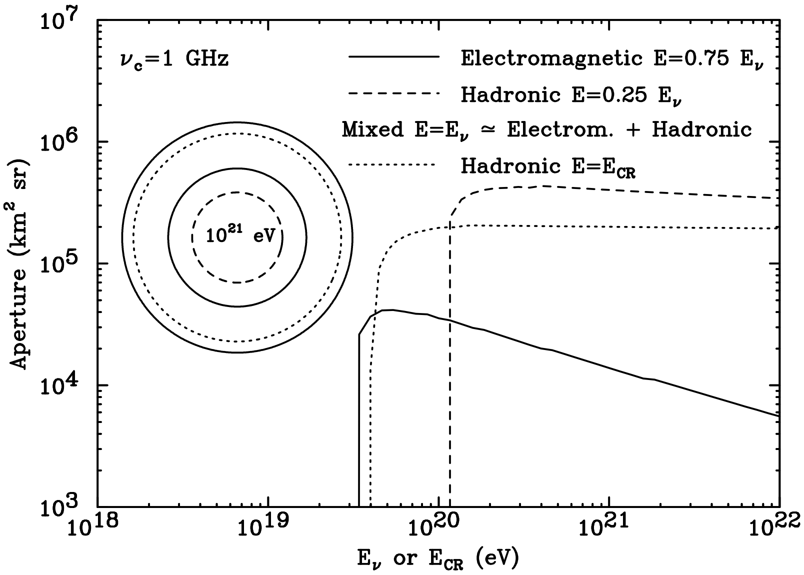

FIGURE 4. Aperture of the Moon for cosmic ray and neutrino detection. For neutrino initiated mixed showers the aperture is the sum of the solid and dashed curves (not drawn). The inset represents the surface of the Moon. The lines correspond to the same lines in the legend. The region between each line and the outermost solid line is the surface where cosmic ray or neutrino detection is expected at $E = 10^{21}$ eV.

which we have extended, perhaps conservatively, to the highest energy observed event (3×10^{20} eV) using a differential slope $\gamma \sim -2.7$. It is clear from the figure that cosmic ray events are going to dominate the event rate near the rim of the Moon outnumbering the neutrino events at least for the representative neutrino fluxes we have chosen. It is then advisable to point the radiotelescopes towards the center of the Moon to be able to observe neutrino events. Due to their high angular resolution, the radiotelescopes such as Goldstone DSS 14 or Parkes in Australia, are able to observe roughly 10% of the surface of the Moon at once, hence one should multiply the numbers in Fig.5 by a factor of 0.1, to get an estimate of the sensitivity of the existing instruments and the observation time required to collect a certain number of events. Our estimates indicate that Goldstone DSS 14 should roughly expect 1 cosmic ray event every 80 hours of observation.

IMPROVEMENTS AND CONCLUSIONS

There are still a few issues that should be explored. The roughness of the surface of the Moon should be included in the calculation. Its wrinkles may facilitate the detection of signals emitted at the Cherenkov angle since, in this case, the particle tracks skimming the regolith surface are in general not parallel to the local surface which creates a problem of total internal reflection. Since showers

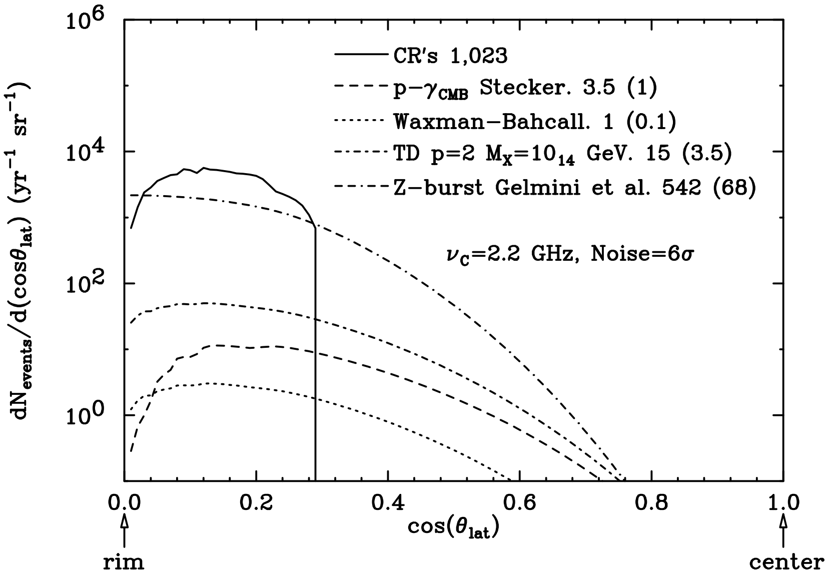

FIGURE 5. Cosmic ray and ν_e CC + ν_e NC + ν_μ CC+NC events in the Moon expected in the NASA/JPL Goldstone DSS 14 radiotelescope. The events are shown as a function of the cosine of the latitude of the points on the surface of the Moon, namely $\cos(\theta_{\rm lat}) = 1$ corresponds to the center of the Moon and $\cos(\theta_{\rm lat}) = 0$ to the outermost rim. One should understand this plot as having azimuthal symmetry around $\cos(\theta_{\rm lat}) = 1$. The numbers accompanying the legends are the total events per year. The numbers in parenthesis represent the neutrino events per year from the latitudes where cosmic ray events are not expected. For cosmic rays the number of events below 3×10^{20} eV is shown.

should be produced near the surface of the Moon, one should worry about near-field effects in the Cherenkov emission [30]. Their main consequences are a decrease of the normalization of the electric field at the Cherenkov peak accompanied by an increase of the width of the Cherenkov cone $\Delta\theta$ [31]. These two effects act in opposite directions with respect to the behavior of the event rate. A decrease in $\Delta\theta$ will increase the effective solid angle while the decrease in the normalization increases the energy threshold. There are also some issues dealing with showers produced at a distance to the surface of the Moon smaller than a radiation length so that Cherenkov radiation doesn't have enough distance to form. Variations of the index of refraction near the surface of the Moon have been measured and should also be included in the calculation of the geometry. Work is in progress to estimate the importance of all these potential issues and the results will be published elsewhere.

Although some room for improvement does exist, we have identified and correctly taken into account many of the elements entering in this difficult problem, updating previous estimates [18]. The actual potential of the Moon as a detector of high energy cosmic rays and neutrinos depends on a comprehensive study of all the elements indicated in this paper and possibly others. In any case, our results are encouraging and should trigger more theoretical work on this exciting possibility.

ACKNOWLEDGEMENTS

We thank Ricardo Vázquez for many discussions on this work. We thank P. Gorham and D. Saltzberg for an excellent and stimulating workshop. We acknowledge the suggestions made by some of the participants: D. Besson, G. Gelmini, P. Gorham, F. Halzen, K. Liewer, D.W. McKay, C. Naudet, J.P. Ralston, D. Saltzberg and I. Zheleznykh among others. The research activities of J.A-M at Bartol Research Institute are supported by the NASA grant NAG5–7009. This work was also supported in part by the European Science Foundation (Neutrino Astrophysics Network N. 86), by the CICYT (AEN99-0589-C02-02) and by Xunta de Galicia (PGIDT00PXI20615PR).

REFERENCES

1. M. Nagano, A.A. Watson, Rev. Mod. Phys. **72** (2000) 689 and refs. therein.
2. F.W. Stecker et al., Phys. Rev. Lett., **66** (1991) 2697.
3. R. Engel and T. Stanev, astro-ph/0101216.
4. F. Halzen, Phys. Rep. **333-334** (2000) 349.
5. P. Bhattacharjee, G. Sigl, Phys. Rep. **327** (2000) 109-247.
6. Design Report of the Pierre Auger Coll., Fermilab Report, Feb. 1997 and refs. therein.
7. D. Cline, F.W. Stecker, contributed to OWL/AW Workshop on Observing Ultrahigh Energy Neutrinos, Los Angeles, California, Nov. 1999, astro-ph/0003459.
8. K. Arisaka for the EUSO collaboration, see these proceedings.
9. T.K. Gaisser, F. Halzen, T. Stanev, Phys. Rep. **258** (1995) 173 and refs. therein.
10. J.G. Learned and K. Mannheim, Ann. Rev. Nucl. Sci. (2000) in press.
11. E. Zas, summary talk given at the *International Workshop on Observing UHECR from Space and Earth*, August 2000, Metepec, Puebla, Mexico, astro-ph/0011414.
12. *Procs. of the* 1^{st} *International Workshop on Radio Detection of High Energy Particles*, Los Angeles, California, November 2000, to be published by AIP.
13. D. Besson et al. see this proceedings; G.M. Frichter *Proc. of the XXVI Int. Cosmic Ray Conference*, Salt Lake City, Utah, July 1999, Vol. 2, p. 467.
14. M. Chiba, see these proceedings.
15. R.D. Dagkesamansky and I.M. Zheleznykh, Pis'ma Zh. Eksp. Teor. Fiz. [JETP Letters] **50**, 233 (1989).
16. T.H. Hankins, R.D. Ekers, J.D. O'Sullivan, Mon. Not. R. Astr. Soc. **283** (1996) 1027.
17. P.W. Gorham, K.M. Liewer, C.J. Naudet. *Proc. of the XXVI Int. Cosmic Ray Conference*, Salt Lake City, Utah, July 1999, Vol. 2, p. 479, astro-ph/9906504.
18. J. Alvarez-Muñiz, E. Zas, *Proc. of the XXV Int. Cosmic Ray Conference*, Durban (South Africa) August 1997, Vol. 7, p.309.
19. L. Landau and I. Pomeranchuk, *Dokl. Akad. Nauk SSSR* **92** (1953) 535; **92** (1935) 735; A.B. Migdal, Phys. Rev. **103** (1956) 1811; Sov. Phys. JETP **5** (1957) 527.
20. J. Alvarez-Muñiz, E. Zas, Phys. Lett. B **411** (1997) 218.
21. J. Alvarez-Muñiz, E. Zas, Phys. Lett. B **434** (1998) 396.

22. J. Alvarez-Muñiz, R.A. Vázquez and E. Zas, Phys. Rev. D **61** (1999) 023001.
23. G.A. Askar'yan, Soviet Physics JETP **14, 2** (1962) 441; **48** (1965) 988.
24. D. Saltzberg, P. W. Gorham, D. Walz, C. Field, R. Iverson, A. Odian, G. Resch, P. Schoessow and D. Williams, submitted to Phys. Rev. Lett., hep-ex/0011001.
25. E. Zas, F. Halzen, T. Stanev, Phys. Rev. D **45** (1992) 362.
26. For detailed information see *http://gts.gdscc.nasa.gov/*
27. R. Gandhi, C. Quigg, M.H. Reno, I. Sarcevic, Phys. Rev. D **58** (1998) 093009.
28. G. Gelmini and A. Kusenko, Phys. Rev. Lett. **84** (2000) 1378.
29. E. Waxman and J. Bahcall, Phys. Rev. D **59** 023002 (1998) 023002.
30. R. Buniy and J.P. Ralston, astro-ph/0003408.
31. J. Alvarez-Muñiz, R.A. Vázquez and E. Zas, Phys. Rev. D **62** (2000) 063001.