UHE Cosmic Rays and Neutrinos Showering on Planet Edges

D. Fargion, P. Oliva, O. Lanciano,
Physics Department and INFN, Universita’ La Sapienza, Roma, Ple. A. Moro 2,00185, Italy

Ultra High Energy (UHE) Cosmic Rays, UHECR, may graze high altitude atmosphere leading to horizontal upward air-showers. Also PeVs $\nu_e$ hitting electron in atmosphere may air-shower at $W^-$ boson resonant mass. On the other side ultra high energy muon and electron neutrinos may also lead, by UHE neutrinos mass state mixing, to the rise of a corresponding UHE Tau neutrino flavor; the consequent UHE tau neutrinos, via charge current interactions in matter, may create UHE taus at horizons (Earth skimming neutrinos or Hor-taus) whose escape in atmosphere and whose consequent decay in flight, may be later amplified by upward showering on terrestrial, planetary atmospheres. Indeed because of the finite terrestrial radius $R_\oplus$, its thin atmosphere size ($h_0 \simeq 10$) km, its dense crust, the UHE tau cannot extend much more than $\sim \sqrt{R_\oplus h_0 \pi/2} \simeq 360$ kilometers in air, corresponding to an energy $E_{\nu_\tau} \simeq 7.2$ EeV, near but below GZK cut-off ones; on the contrary Jupiter (or even Saturn) may offer a wider, less dense and thicker gaseous layer at the horizons where Tau may loose little energy, travel longer before decay and rise and shower at $E_{\nu_\tau} \simeq 4 - 6 \cdot 10^{19}$ eV or ZeV extreme energy. Also solar atmosphere may play a role, but unfortunately tau-showers secondaries maybe are too noisy to be disentangled, while Jupiter atmosphere, or better, Saturn one, may offer a clearer imprint for GZK (and higher Z-Burst) Tau showering, well below the horizons edges.

1. Past Neutrino Telescope Underground

UHE Neutrino detection and Astronomy is a compelling cornerstone in Astrophysics, possibly correlated to UHECR Astronomy \[21\], just nearby GZK cut-off \[30\]. Most of past and present $\nu$ detector are tracing muon in underground detectors \[2\], \[1\]. This because of proliferous, penetrating nature of the muon. Due to the neutrino flux paucity and its low cross-section most of the detector are large as Super Kamiokande or larger volumes as AMANDA, Baikal or Antares ones, looking to km$^3$ future size \[20\]. Because most of cosmic rays are converting into atmospheric muon secondaries, the muon dawn ward directions are polluted by atmospheric noises. The upward muons, induced by UHE neutrinos charged currents are suppressed because of their parental neutrinos opacity to Earth sizes, above 40 TeV energy range. This energy unfortunately lays where astrophysical neutrinos might dominate over atmospheric ones. Horizontal Muons might be a better tools for UHE $\nu$ astronomy, but most km$^3$ detectors are basically vertical string unable to disentangle horizon directions. However a novel way to observe UHE neutrinos has been proposed since almost a decade \[9\] and revived on recent years \[11\], \[13\], \[16\], \[4\], \[27\], \[10\], \[17\] and \[25\]; it is based on horizontal skimming neutrinos whose consequent UHE $\tau$ air-showering by decay in flight in air invade large detection areas. The energy windows for Tau Astronomy opens at PeV up to few EeV energy band which is of great interest.

2. Atmosphere sizes versus $\tau$ tracks-energy

Either UHE neutrino skimming showering in air or up-going UHE tau neutrino interacting within Earth, may be leading to skimming parent $\tau$ well amplified by a decay and a shower in flight. The phenomena of such $\tau$ air-showers remind the double-bang signature \[24\] for $\nu_\tau$ interaction and soon later $\tau$ decay in water. Here we assume one bang in and the second bang out. The simplest case of a mountain Chain (like Ande) acting as a target for UHE neutrino has been first considered \[9\], while later the Earth itself has been proposed as a beam dump at its edges \[11\], \[15\]. Their signal is amplified and spread in huge number of secondaries over wide areas. The $\nu_\tau \to \tau$ conversion
Figure 1. Long High Altitude Horizontal Air-showers versus vertical ones: here we assumed a PeV-EeV C.R. and we schematically draw the narrower beaming and the geomagnetic splitting of the showers; the moon size from the Space Station at Horizons is used as a ruler. A very rare (neutrino induced) Tau air Shower may point upward within a noisy free Earth shadows, coming from below the horizons into observable Tau Shower may reach high efficiency at the horizontal atmosphere edges, otherwise (in upward vertical directions) their parental UHE neutrinos suffer of severe planet opacity. The EeVs UHE tau shower secondary (UV-X-Gamma-Muon Bundle) discover from Earth is already at hand either by top mountains telescope as Magic ones, or by sharp anisotropy in Horizontal Showers within Auger Ande shadows, or by present and future satellites (like Swift, Glast and future ideal Array detectors in Space Station, see Fig. 1 facing the Earth); these showering reminds the eventual PeVs $\bar{\nu}_e$ hitting electron at $W^-$ boson resonant mass. In analogy hypothetical UHE SUSY neutralino may be scattering atmosphere electron at tens PeVs resonant energy for $\bar{\nu}_e$ s-channel, arriving above the horizons [6]. At higher altitudes UHECR may skim the terrestrial or other planetary atmosphere leading to thin collimated air-showers whose structure is not just like conical vertical ones, see Fig. 1 but they often split in twin jets by geomagnetic fields [10]. A simple analogous gamma originated grazing mechanism may play a role by converting unobservable hard GeV-TeV or PeVs gamma astronomy: while such hard photons are skimming highest quota they are showering in terrestrial, planetary or solar atmosphere altitudes; their skimming secondaries produce a cylindric cone that may be intersect by a satellite trajectory. These rises and dawns at the horizons of hard source into softer one, might lead to transient X sources whose set and re-appearance time may exhibit characteristic terrestrial (orbital) lag modulation see Fig. 2.

While the UHE neutrino skimming the Earth produces an escaping tau, the consequent decay in flight is constrained by the size of the planet gas layers: on Earth the height size $h_0 \simeq \sqrt{R_\oplus h_0 \pi/2}$ imply a maximal distance $d_{\tau\oplus} \simeq \sqrt{R_\oplus h_0 \pi/2} \simeq 360$ km. The corresponding maximal tau energy is $E_{\tau\oplus} \simeq \frac{d_{\tau\oplus}}{(c\tau_{\bar{\nu}_e})}m_\tau c^2 \simeq 7.2$ EeV. To visualize Horizontal Air-Showers versus vertical ones and upward Hortau see Fig. 2.

The larger the planet size $R$ and the wider its density height scale $h_0$, the larger is the allowed distance $d_\tau$ for the Tau to fly before decay (and...
the higher its correlated energy). The atmosphere and the planet density profile rule also the penetrability of the UHE primary neutrino. The case for the Earth has been carefully analyzed in recent papers ([15] and [16]) and will be reminded later.

2.1. Inner Planets atmospheres

The nearest planet as Mercury do not offer an atmosphere as the most distant ones. Therefore we consider for skimming UHECR and Tau showering in inner planets Mars and Venus. The Venus distance $d_\tau$ at horizon is wider by 40% respect the Earth one: $d_\tau \simeq \sqrt{R_{\oplus}h_0\pi/2} \simeq 1.4\ d_{\tau\oplus} = 504$ km corresponding to a maximal tau energy $E_\tau \simeq [d_\tau/((c\tau_d)]m_\pi c^2 \simeq 10$ EeV . On the other side, the Mars air density is too small ($\simeq 1\%$ of earth one) to be of great interest for UHECR or EeV neutrinos induced showers. Moreover the Mars radius in nearly half of the terrestrial one, (but its height scale is a little longer): $d_\tau \simeq \sqrt{R_{\oplus}h_0\pi/2} \simeq 0.855\ d_{\tau\oplus} = 308$ km, corresponding to a smaller tau energy $E_\tau \simeq 6$ EeV, anyway undetectable by Mars thin atmosphere. Indeed only PeV or TeV cosmic rays might shower at maximal size at martian horizon. This possibility may be used in gamma astronomy, if future telescope on Mars will consider this kind of astronomy. Nevertheless such a low density atmosphere occurs already in high altitude balloons near Earth or in highest altitude for skimming gamma at top terrestrial altitudes.

3. The Tau length $l_\tau$ in Outer Planets

The parameter that must be correlated with the planet size is the propagation length $l_\tau$, see Fig. 3. The great advantage of largest gaseous planets in UHE tau-showering is three fold: their size is wider, their height scale is longer and their external density profile are more diluted that terrestrial ones, offering in this way an extreme windows to maximal neutrino energies.

The nearest Jupiter planet, see Fig. 4 exhibit the largest radius and it surge as the leading planet for largest $l_\tau$. Indeed its radius, $R_J =$
Figure 5. Schematic Showering in atmosphere (for Ultra High Energy Cosmic Rays) and inside the Saturn edges by $\nu_\tau$ charged current neutrino interaction and its consequent $\tau$ decay in flight. The large planet radius and its longest atmosphere height size makes these $\tau$ flights the longest ones observable in our planetary system. Also very peculiar UHECR showering takes place also along the thin Saturn disk edges.

71492 km, is eleven times the Earth radius, while the atmosphere height $h_{0J} = 3.4 h_{0\oplus}$. Therefore the consequent maximal horizontal distance is $d_{\tau J} \simeq \sqrt{R_J h_{0J} \pi/2} \simeq 6.15 d_{\tau \oplus} = 2214$ km, while $h_{0J} \simeq 3.37 h_{0\oplus}$, corresponding to a maximal tau energy $E_{\tau J} \simeq [d_{\tau J}/(c\tau)]m_\tau c^2 \simeq 4.43 \cdot 10^{19}$ eV.

Surprisingly the best planet for largest tau distances is not Jupiter but the nearby Saturn Fig. 5: the radius $R_S$ is slightly smaller, but its height atmosphere scale is quite larger. Indeed the Saturn radius $R_S = 60268$ km, is only 9.4 times our planet radius, but the atmosphere height scale $h_{0S}$ (see dotted line in Fig. 6) applied in Fig. 3, as better compared in density profile Fig. 7, is 7.4 times the terrestrial $h_{0\oplus}$. Therefore the resulting $d_{\tau S} \simeq \sqrt{R_S h_{0S} \pi/2} \simeq 8.38 d_{\tau \oplus} = 3017$ km, is the largest in our planetary system. Then the maximal energy for tau is $E_{\tau S} \simeq [d_{\tau S}/(c\tau)]m_\tau c^2 \simeq 6 \cdot 10^{19}$ eV. As it is shown in Fig. 8 where Saturn size distance (dotted line) intersect with the tau boosted fly distance. The case of Uranus and Neptune planets are comparable (but of less interest) because of their smaller sizes and smaller height density growth, as well as because of their larger distances from us. Moons around planets are usually with null atmosphere except for a Saturnian moon, Titan, of great and peculiar atmosphere density.

3.1. The Titan Role in UpTaus showering

One of the critical role of Tau Air-Showers is the parental UHE $\nu_\tau$ opacity crossing along the planet cord. The opacity is related to the electro-weak cross-section dependence on incoming neutrino energy with matter [20] and, of course, on the planet size and composition. Smallest radius allows greater neutrino energy: for the Earth diameter the neutrino cut-off is about $4 \cdot 10^{13}$ eV for $\nu_\mu$ and $10^{15}$ eV for $\nu_\tau$ (because of their marginal regeneration and pile up by higher energies neutrinos toward PeV band). For this reasons Horizontal Tau at tens PeV or EeV are possible as well as up-taus just at PeV energies on Earth (or with a partial suppression [15]).

Naturally Titan being just 5150 km size and 1.88 average density allows higher energy neutrino crossing, because in vertical direction (slant depth $X_{\text{max}} = 9.68 \cdot 10^8$ w.e.) the out-coming energy (see Fig 8 maybe unsuppressed even a hundred times at higher values: $E_{\tau \text{min}} \simeq 5 \cdot 10^{15}$, see Fig 10) in principle a much better screen to look for Up-Taus showering in the future search.
of UHE $\nu_\tau$ in space. Finally up-ward and inclined tau air-shower at Titan may enjoy of the longer atmosphere height scale (respect to Earth), which is $h_{0,\text{Titan}} \simeq 30$ km, see Fig. 8, leading to better contained upward showering event at $10^{17} - 10^{18}$ such air-showers are deep valleys (to enhance the solid angle of the tau air-showers), peak mountains, balloons, planes and satellites facing the Earth. In UHE neutrino and $\tau$ showering search different experimental frame-work might be used: Cherenkov telescope and arrays, Scintillator and C.R. arrays facing Mountains or the Earth edges. See Fig. 11, [14]. Cherenkov gamma Telescopes like MAGIC ones at the top of a mountains are searching for tens GeV $\gamma$ astronomy. The same telescope at zero cost in cloudy nights, may turn (for an bending angle $\simeq 10^\circ$) toward terrestrial horizontal edges, testing both common PeVs cosmic ray air showers and UHE showering in air, see Fig. 12. In upward directions muon and-or gamma secondary bundles by up-going tau air-showers might blaze the Telescope, see Fig. 13. The peculiar Magic position on the sea offer the geometry for reflected downward CR on the water. The absence of correlated muon bundle and the presence of a polarization in Cherenkov lights make a clear signature of these mirrored events. Indeed the possible detection of a far (un-mirrored) air shower is enriched by: 1) early Cerenkov flash even if dimmed by atmosphere screen, 2) single and multiple muon bundle shining Cerenkov rings or arcs inside the Magic disk in time correlation.

4. Back to the Earth: Magic and Auger

Naturally the simplest and nearest and most practical way to look for UHE neutrinos showering at PeVs energies or above is facing the Sky of our Sky: the Earth. The possible way to trace
Figure 10. The interaction length for UHE neutrinos as a function of their energy, crossing the Earth (green dot-dashed line) and Titan (red dashed line).

Figure 11. Ideal arrays of Cherenkov Crowns Telescopes in Canaries [14] and an equivalent twin Crown Array Balloon in flight; similar arrays maybe located in planes or satellites.

3) muon decaying into electromagnetic in flight making mini showers mostly outside the disk leading to lateral correlated gamma tails. We estimated the rate for such PeVs-EeV events each night, finding hundreds event of noises muons and tens of bundle correlated signals each night [17], [18] at horizons. Among them up-going Tau Air-Shower may occur very rarely, but their discovery is at hand for dedicated 360° crown Arrays on Mountains (see Fig 11) [14] or in Space (see Fig 15) in correlation among Cherenkov and additional scintillator detectors. The UHECR and UHE neutrino astronomy at horizons may test the expected GZK [30] neutrino traces and eventual Z- Burst UHE neutrino parental spectra at highest energy edges [31], [29], [26].

5. Conclusions

The search for UHECR and UHE neutrino Astronomy is compelling: the puzzles they may solve are fundamental. While UHE neutrino telescope underground are still seeking rare single muon tracks, UHE tau air-shower Astronomy may amplify the neutrino and the UHECR skimming the Earth or the top atmosphere. The tau length is related to the UHE neutrino energy and to allowable air layer on Earth. New opportunities arise in outer planets as Jupiter and Saturn, whose radiiuses and whose height scale afford huge
distances and largest tau energies. A very peculiar case arise around the small, but denser Titan atmosphere able to permit up-tau at energies (tens PeV) very favorable for UHE neutrino astronomy. However just to begin the Earth from mountains, in deep valleys and on balloons and space is the most actual place to play the search for this novel Astronomy. The Auger shadows from the Ande might hide a couple of event each year while Magic Telescope might rush in Horizons edges at GRB event. Even satellites like Pamela and Glast might test up-going showers as Terrestrial Gamma Flashes whose nature might be already associated to UHECR or Tau showering skimming the Earth.

REFERENCES
1. Anchordoqui L., Halzen F. hep-ph/0510389
2. Bhattacharjee et al. Phys.Rept. 327 (2000) 109-247.
3. Bertou, X. et. al. 2002, Astropart. Phys., 17, 183
4. Cao Z., Huang M.A., Sokolsky P., Y. Hu, J.Phys. G31(2005)571-582
5. Cronin, J.W. astro-ph/0402487, www.pi.infn.it/lathuile/2006/talks/cronin.pdf
6. Datta A., Fargion D., Mele B. JHEP09(2005)007
7. Dutta S.I., Huang Y., Reno M. H. hep-ph/0504208
8. Fargion, D., Mele, B., Salis, A., 1999, ApJ 517,725; astro-ph/9710029
9. Fargion, D., Aiello, et all. 1999, 26th ICRC, HE6.1.10,396-398
10. Fargion, D. 27th ICRC 2001, HE1.8, Vol-2, Germany, Pag. 903-906.
11. Fargion, D., 2002, ApJ, 570, 909; see
12. Fargion, D. et.all. 2003, Recent Res. Devel.Astrophysics., 1, 395
13. Fargion, D., F. Moscato, Chin. J. Astron. Astrophys. Vol 3.Supp. 75-86. 2003.
14. Fargion, D., et all. Adv. in Space Res., 37 (2006) 2132-2138.
15. Fargion, D., et all. 2004, ApJ, 613, 1285.
16. Fargion, et al., Nuclear Physics B (Proc. Suppl.) 2004, 136, 119
17. Fargion, D. astro-ph/0511597; Prog. Part. Nucl. Phys. 57, 2006, 384-393
18. Fargion, D. astro-ph/0607526/0604430
19. Feng, J.L., Fisher,P., Wilczek, F., Yu T.M., 2002, Phys. Rev. Lett. 88, 161102
20. Gandhi, R., Quigg, C., Reno, M.H, Sarcevic, I. 1998, Phys. Rev. D 58, 093009
21. Grieder, P.K.F., Cosmic Rays at Earth, Elsevier 2001
22. Jones, J. et all. 2004, Phys. Rev. D, 69, 033004
23. Justus, C.G. et all. Planetary and Space Science, 2005, 53, 601-605
24. Learned, J.G., & Pakvasa, S., 1995, Astropart. Phys., 3, 267
25. Miele, G., Pastor, S., Pisanti, O., astro-ph/0508038
26. Quigg, C. astro-ph/0603372
27. Tseng, J.J., Yeh, T.W., Athar et all. 2003, Phys. Rev. D 68, 063003
28. Yoshida, S., et all, 2004, Phys. Rev. D 69, 103004.
29. Yoshida, S., et all. Phys. Rev. Lett. 81, 1998, 5505-5508.
30. Zatsepin, G.T. and Kuz’min, V.A., Zh. Eks. Teor. Fiz., Pis’ma Red. 4 (1966) 144.