Multimessenger search for point sources: ultra-high energy cosmic rays and neutrinos

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The origin of ultra-high energy cosmic rays (UHECRs) and neutrinos is still a mystery. Hadronic acceleration theory suggests that they should originate in the same sources (astrophysical or cosmological), together with gamma-rays. While gamma-rays have been linked to astrophysical sources, no point source of UHECRs or neutrinos have been found so far. In this paper, the multimessenger combination of UHECRs and neutrinos as a new approach to the high energy particle point source search is suggested. A statistical method for cross-correlation of UHECR and neutrino data sets is proposed. By obtaining the probability density function of number of neutrino events within chosen angular distance from observed UHECRs, the number of neutrino events in the vicinity of observed UHECRs, necessary to claim a discovery with a chosen significance, can be calculated. Different angular distances (bin sizes) are considered due to the unknown deflection of cosmic rays in galactic and intergalactic magnetic fields. Possible observed correlation of the arrival directions of UHECRs and neutrinos would provide a strong indication of hadronic acceleration theory. Correlation of both types of messengers with the location of certain sets of observed astrophysical objects would indicate sites of acceleration. Any systematic offset in arrival directions between UHECRs and neutrinos may shed more light on magnetic field deflection of cosmic rays.

1 Introduction

The origin of high energy particles coming from the Universe is still not known. Currently, it is suggested that cosmic rays (protons and nuclei) up to about $10^{15}$ eV gain their energy in acceleration by shocks from supernova explosions (see for example Nagano & Watson 2000). For cosmic rays with energies around $10^{16} - 10^{17}$ eV, it has been suggested that acceleration can occur in the interaction of particles with multiple supernova remnants (Ip & Axford 1991), galactic wind (Völk & Zirakashvili 2004), and microquasars (Mirabel 2008). The highest energy charged cosmic rays are expected to be of extragalactic origin and get accelerated in jets of gamma-ray bursts (Waxman 1995, Vietri 1995) or active galactic nuclei (Biermann & Strittmatter 1983, Rachen & Biermann 1993). Another option are so-called top-down scenarios: protons and neutrons, but also neutrinos and gammarays, are produced from quark and gluon fragmentation of heavy exotic particles formed in the early Universe (Hill 1983, Schramm & Hill 1983). According to the theory of hadronic acceleration, the ultra-high energy cosmic ray (UHECR) flux is expected to be accompanied by associated fluxes of gamma-rays and neutrinos from pion decays formed in the collision of protons with photons (for example see Zas 2005).

When a cosmic ray interacts with a particle in the Earth’s atmosphere, a shower of particles is produced propagating towards the ground with almost the speed of light. These so-called "cosmic ray air showers" can be detected by arrays of Cherenkov detectors, fluorescent detectors or radio antennas. Low energy cosmic rays are constantly bombarding the Earth producing such showers, but cosmic rays of energies above $10^{19}$ eV are very rare. They are expected to occur less than once a year on an area of one square kilometer and large shower arrays like the Pierre Auger Observatory ($3000$ km$^2$) are needed. Moreover, cosmic rays are deflected by magnetic fields on their way from source to the Earth, thus their arrival...
directions do not point back to their sources. The expected deflection due to the Galactic magnetic field is in the order of few degrees for ultra-high energy protons (Tinyakov & Tkachev 2005). Also, it is not yet known whether large deflections are caused by extra-galactic magnetic fields. According to some authors (Dolag et al. 2005), they are in the order of one degree and below, but some other analysis are predicting far larger numbers (Sigl et al. 2004). The highest energy cosmic rays are expected to be suppressed by interaction with the cosmic microwave background radiation, which is known as the Greisen-Zatsepin-Kuzmin (GZK) cut-off (Greisen 1966; Zatsepin & Kuzmin 1966). Due to this effect, they can be observed only if they originate in sources closer than about 200Mpc. Note that the size of the GZK sphere is still under discussion, and significantly smaller GZK spheres are suggested by some authors (see for example Becker 2008). The HiRes experiment (Abbasi et al. 2004) measurements are in agreement with the predicted flux suppression of the highest energy cosmic rays, however the results of the AGASA experiment (Takeda et al. 1998) show an excess compared to the predicted GZK suppression (Bahcall & Waxman 2003). The Pierre Auger collaboration reported recently observations consistent with GZK cut-off (The Pierre Auger Collaboration 2008).

Neutrinos are difficult to detect due to their small cross section for interaction with matter. They can interact within the Earth’s atmosphere and trigger air showers. The probability for interaction increases with the path length, thus they are most likely to produce very inclined cosmic ray air showers. Those showers may be triggered anywhere along the traveling path and also close to the ground (Capelle et al. 1998). However, a neutrino is much more likely to undergo charged current interaction with nuclei in the Earth’s interior, producing a muon that emits Cherenkov radiation while moving through water or ice faster than the speed of light in the corresponding medium. This principle is used in current neutrino telescopes, such as IceCube and ANTARES. The IceCube neutrino telescope is currently being built at the South Pole. The final configuration should reach around 80 strings with photomultiplier tubes (PMTs) in a 1km$^3$ geometric volume. Currently, data are being taken with 40 strings. ANTARES was recently finished in the Mediterranean Sea close to the French coast. Its final configuration consists of 12 strings with PMTs in 0.03km$^3$ of instrumented volume. The largest problem for observation of cosmic neutrinos is the large atmospheric flux of secondary neutrinos coming from air showers. Comparing to UHECRs, the advantage of neutrinos as messengers is that they are not deflected in magnetic fields, so their arrival direction point back to their sources. The neutrino interaction cross section increases with increasing energy, so the highest energy neutrinos are more likely to interact with the detector, but also within the Earth’s interior. This means that neutrinos above around 1PeV can be observed only if coming from horizontal directions, so their path through the Earth interior is shorter.

2 Cross-correlation of neutrinos and cosmic rays

The Pierre Auger Observatory reported an anisotropy in the arrival directions of ultra high energy cosmic rays (The Pierre Auger Collaboration 2008). Correlation with Active Galactic Nuclei (AGN) from the VCV catalog (Véron-Cetty & Véron 2006) was the most significant for cosmic rays with energies higher than 57EeV and

![Figure 1: Aitoff skyplot of 27 UHECR events with E>57EeV (squares) observed by the Pierre Auger Observatory and AGNs from the VCV catalog at D<75Mpc (diamonds) in equatorial coordinates. The color code represents the redshift of AGNs, with purple being the closest and red being the furthest objects. The dashed line represent the supergalactic plane (plot after The Pierre Auger Collaboration (2008)).]
AGNs at distances less than $75 \text{Mpc}$. For this correlation, an angular separation between AGNs and cosmic rays larger than the point spread function of the detector is considered, so magnetic deflection of cosmic rays is in this way partially taken into account. However, the mass composition of the observed events is not yet established, and the possible deflection in magnetic fields is not yet known. This means that in the case that the observed events are mostly nuclei, their arrival directions may significantly differ from the directions of their acceleration sites. The anisotropy was estimated with a confidence level of 99%. The suggested correlation with local AGN sources mostly following the location of the supragalactic plane decreased in the following analysis (The Pierre Auger Collaboration 2009) with 58 events observed at energies above $55 \text{EeV}$. The anisotropy of observed events remains with a confidence level of 99%. On the other side, no significant excess above the atmospheric neutrino flux was reported by the neutrino telescopes IceCube and ANTARES (IceCube Collaboration: R. Abbasi 2009; Toscano & the ANTARES collaboration 2009).

Instead of searching for such a localized excess, neutrino arrival direction can be correlated with the arrival directions of ultra high energy cosmic rays. In this paper, a method is suggested for such a correlation. The described analysis is based on the calculation of the probability density function of the number of neutrino events within specific angular distances from UHECRs. For a given set of observed cosmic ray arrival directions that are used as a catalog, Monte Carlo neutrino sets are generated, and angular distances between all cosmic rays and all MC neutrinos are calculated, (full sky correlation). In this way we obtain neutrino counts in chosen bins around the observed UHECRs, expected only from the atmospheric background neutrino flux. In other words, we calculate the probability that any neutrino count appears in the observed data. Usually, the bin size for this kind of analysis is the angular resolution of the detector, but due to the unknown deflection of cosmic rays in magnetic fields, we leave this parameter free. This allows our analysis to be sensitive for a potential systematic offset between arrival directions of ultra-high energy cosmic rays and neutrinos.

An example for the calculation of the probability density function of the number of neutrino events within specific angular distances from UHECRs is presented. Fixed 27 UHECR events are used as catalog sources. Monte Carlo simulations with 1000 neutrinos on each generated sky map, randomly distributed over the full sky (declinations $[90^\circ,-90^\circ]$ and right ascension $[0^\circ,360^\circ]$) are performed. Further, angular distances between all Monte Carlo neutrinos and 27 UHECRs are calculated, for each produced sky map. This provides the expected angular distance distribution between neutrinos and cosmic rays in the absence of any correlation, over the whole sky. For a specific neutrino telescope, such as ANTARES or IceCube, instead of the whole sky, only declinations...
Figure 3: Probability density function of the number of neutrino events on \(1^\circ, 2^\circ, 5^\circ\) and \(10^\circ\) angular distances from 27 fixed UHECR, for 1000 random background neutrinos.

visible by the chosen detector should be used, and instead of a completely random neutrino background distribution, one that corresponds to the detector exposure should be applied. Also, the actually observed number of neutrino events should be used for Monte Carlo calculations. Correlation should be performed on a part of sky visible for both UHECR and neutrino detector. Fig. 2 shows the combined fields of view for the Auger observatory and the ANTARES telescope (left panel) and the Auger observatory and the IceCube telescope (right panel). The Auger observatory is located at \(35^\circ\)S, and declinations up to \(55^\circ\) are observable. However, for the observed UHECR, an additional cut on zenith angle of \(60^\circ\) is added, which means that declinations up to about \(25^\circ\) are visible. The ANTARES telescope is located at \(43^\circ\)N, and for up-going events, declinations up to \(47^\circ\) are visible. The IceCube detector is at the South pole, so everything above \(0^\circ\) declination is in the field of view. IceCube is also investigating the possibility of extended sky search, by using also down-going events, and in that case all declinations above around \(-50^\circ\) are observable (Lauer & the IceCube Collaboration 2009).

Using this probability density function, the expected number of neutrino events in the vicinity of the observed ultra-high energy cosmic rays, necessary to claim a discovery with a chosen significance, can be calculated. Even though the expected angular resolution for IceCube and ANTARES is better than 1 degree, bin sizes of 1-10 degrees are considered. This is because UHECRs may be deflected significantly in magnetic fields on their path to the Earth, thus the analysis is sensitive to a possible offset between arrival directions of cosmic rays and neutrinos.

Probabilities for the expected number of background neutrinos, in bins around the 27 fixed UHECR events are shown in Fig. 3. For example, the probability to observe 1 neutrino, within 27 bins of \(1^\circ\) is around 26%, and the probability to observe 5 neutrinos within those bins is around 3%. The probability to not have any neutrinos is around 14%, and to have more than 8 is close to zero. The same distributions are shown for bin sizes of 2.5 and 10 degrees. This can be translated into discovery potential and the number of neutrino events within a certain distance from observed cosmic rays, necessary to claim a discovery, can be obtained.

Depending on Monte Carlo statistics, the number of neutrino events in the vicinity of cosmic rays, needed for a 3, 4 or \(5\sigma\) discovery (correlation) claims can be established. This is shown in the left panel of Fig. 4 for \(10^7\) Monte Carlo simulations, 27 fixed UHECRs, 1000 random neutrinos, and bin sizes of 1-10\(^\circ\). For example, correlation significance of \(3\sigma\) is reached with about 11 neutrino events within 27 bins of \(1^\circ\), \(4\sigma\) with 18 and \(5\sigma\) with 22. The right panel of Fig. 4 shows the percentage of neutrino events necessary for \(5\sigma\) discovery claim, depending on the bin size and the number of UHECRs. The bottom red line corresponds to magenta values presented in the left panel of Fig. 4. It is shown that in the case of 27 UHECRs, correlation significance of \(5\sigma\) is reached with 2%-25% of neutrino events falling in 1-10\(^\circ\) bins. However, with 100 UHECRs, it becomes more difficult to claim \(5\sigma\) discovery for large bins, since 50-100% of neutrino events should be in 5-10\(^\circ\) bins. This becomes even more extreme for 200 and 500 UHECRs, where more than 80% of neutrino events should be already in \(4^\circ\) and \(2^\circ\) respectively, to claim a \(5\sigma\) correlation. This stays the case even if a far larger amount of neutrinos is added (50000). However, it does slightly depend on UHECRs sky distribution, since the exposure for neutrino detection depends on declination. Anyhow, in the case of large number (>100) of observed UHECRs, it is suggested to first group those in clusters, and then apply the described method on centers of those UHECR clusters.

Instead of the full (visible) sky, the UHECR-neutrino
cross correlation can also be applied only on certain regions. The most interesting regions, according to a current Auger results, are Centaurus A and the supergalactic plane due to the observed event excess. Also, the Virgo cluster from where no UHECR was yet observed, should be considered, since it might happen that due to a large magnetic field deflection, events are moved to other arrival directions.

To test the method, fake neutrino sources that coincide with UHECR events are added to the Monte Carlo simulations. In this case, the expected number of neutrinos increases, proportional to the assumed number of neutrino sources coinciding with fixed UHECRs. This is shown in the left panel of Fig. 5. The luminosity of all fake sources is assumed to be 5 neutrinos (Gaussian-distributed around the given arrival direction of a cosmic ray), and the bin size is taken to be 1 degree. For example, the probability of having 5 neutrinos within 27 bins with one fake source is around 20%, compared to 5% with only background neutrinos. With 5 fake sources, the highest probability is to observe around 10 neutrinos in 27 bins. The probability to observe more than 20 neutrinos is beneath 1%. With 10 fake sources, around 20 neutrinos are most likely to be observed, and more than 30 are expected in less than 1% of the cases. The right panel of Fig. 5 shows the expected distributions for 5 fake neutrino sources, with luminosities 5, and exaggerated values of 10 and 20 neutrinos. If the added sources have higher luminosity, the expected number of neutrinos also increases. In other words, as expected, the method recognizes a stronger correlation, when the neutrino sources coincide with the observed cosmic rays and when the neutrino sources are brighter.

3 Discussion

In the previous section, a statistical method for correlation of UHECR and neutrino data sets was described. Possible observed correlation of the arrival directions of those two types of messengers would provide a strong indication of hadronic acceleration theory. Correlation of both types of messengers with the location of certain sets of observed astrophysical objects would indicate sites of acceleration. As we already mentioned, it is currently believed that UHECR are originating in extragalactic sources, gamma-ray burst (GRBs) and active galactic nuclei (AGNs). While gamma-ray bursts (GRBs) are transient extragalactic sources, and more suitable for correlation between gamma-rays and neutrinos (due to a significant delay in the arrival time between protons/nuclei and neutrinos), active galactic nuclei (AGNs), as extragalactic and steady sources, seem like a natural choice to explore the link between UHECRs and neutrinos. Assuming that
there is a GZK cut-off, for an interpretation of correlation between arrival directions of UHECR and neutrinos, the limit should be set on AGNs within the GZK sphere. (left panel of Fig. 6). However, we should keep on mind that AGNs with jets not pointing towards the Earth are possible sources of UHECRs, since they can escape on the sides of jets, but neutrinos follow the direction of the jet and are possible observed only from blazar/BL Lac objects, or ones so close by that they show blazar-like radiation, like it is the case with Centaurus A (right panel of Fig. 6). Due to UHECR excess observed in Cen A region by the Pierre Auger observatory, this region is interesting for UHECR/neutrino link investigation. Neutrino fluxes from Cen A are recently calculated by Koers & Tinyakov (2008) and Becker & Biermann (2009), but if neutrinos are indeed following the direction of jets, neutrino telescopes might not see the signal from this source.

Any systematic offset in arrival directions between UHECRs and neutrinos may shed more light on magnetic field deflection of cosmic rays. The Galactic magnetic field has been shown to have both regular and random components. The regular component is believed to have a spiral structure and the corresponding global model was done by Stanev (1997). According to this model, protons with an energy of about $4 \times 10^{19}$ eV can be deflected by the regular galactic magnetic field around $5^\circ$. Tinyakov & Tkachev (2005) calculated deflection in the random component to be about $0.2^\circ$-$1.5^\circ$ depending on the arrival direction of a $4 \times 10^{19}$eV proton. Dolag et al. (2005) used simulations of the large-scale structure to investigate magnetic fields in the intergalactic medium. They constructed full sky-maps of expected deflections for protons with energies of $10^{20}$ eV and $4 \times 10^{19}$ eV, and found that strong deflections are only present if UHE protons cross a galaxy cluster, and even then stay beneath $1^\circ$. On the other side, Sigl et al. (2004) suggested that deflection in extra-galactic magnetic fields can be of order $20^\circ$ up to $10^{20}$ eV. They suggested that a region of strong magnetic field surrounding the observer would shield off UHECRs from sources outside of the magnetized region, so the observed flux would be dominated by a few closer sources and appear more anisotropic.

4 Conclusions

The hadronic acceleration theory predicts that ultra-high energy cosmic rays are accompanied by neutrino and gamma-ray fluxes. While gamma-rays have been linked with astrophysical sources by observations of telescopes like H.E.S.S. and MAGIC, and several attempts have been made to correlate them with
neutrinos (Hughey & the Ice Cube Collaboration 2007; Ackermann et al. 2008; Bouwhuis 2008), the UHECR-neutrino connection has not yet been examined. The reason is that both UHECRs and neutrinos have many downsides as messengers. UHECRs are rare and they do not point back to their sources, since they are scrambled by galactic and intergalactic magnetic fields. Also, due to the interaction with the cosmic microwave background photons, they might be limited to the distance of about 200Mpc or less. However, they are detectable with large shower arrays, like the Pierre Auger Observatory, which so far reported observation of few tens of events above 55EeV. On the other side, cosmic neutrinos point back to their sources and their traveling distances are not limited, but they interact rarely, which makes them difficult to detect. Also, they are for now lost in the huge atmospheric background of neutrinos coming from air showers, and so far none of the currently operating neutrino telescopes (IceCube, ANTARES) have observed neutrino excess above the atmospheric background flux.

In this paper, the multimessenger combination of UHECRs and neutrinos as a new approach to the high energy particle point source search is suggested. A statistical method for cross-correlation of UHECR and neutrino data sets is proposed. By obtaining the probability density function of the number of neutrino events within specific angular distance from observed UHECRs, the number of neutrino events in the vicinity of observed ultra-high energy cosmic rays, necessary to claim a discovery with a chosen significance, can be calculated. Different bin sizes are considered due to the unknown magnetic deflection of UHECRs. This multimessenger connection is crucial to indicate that hadronic acceleration actually happens in astrophysical sources, since only then neutrinos are to be observed coming from those sources. Through the correlation of arrival directions of those two very different messengers, we can gain additional insight into the non-thermal Universe. In the case of a correlation, we can learn more about the possible sources and physical processes that are responsible for the existence of ultra-high energy particles, such as hadronic acceleration of particles in sources. In the case of an offset between arrival directions of cosmic rays and neutrinos, additional insight in UHECR deflection in magnetic fields can be gained.

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