MAGIC telescopes trace origin of a rare cosmic neutrino

Questions and answers

By Prof. Dr. Elisa Bernardini, DESY (Zeuthen), Germany

What are neutrinos?

Neutrinos are the most elusive elementary particles. They have no electric charge and almost no mass, which allows them to go across dense and thick layers of matter from the most extreme edges of the universe almost without leaving any trace. This makes them very powerful messengers of the history of the universe, but very hard to observe.

Where do neutrinos come from?

An uncountable number of neutrinos reaches the Earth every second. Scientists assume that as many as 60 billions of these particles pass through an area the size of a thumbnail per second – without leaving a trace. Most of the neutrinos, at low energies, come from the Sun and from stellar explosions. At higher energies, neutrinos are produced in local interactions the Earth's atmosphere and are called atmospheric.

Although it is very difficult to detect neutrinos, IceCube is able to register about 200 atmospheric neutrinos per day.

Collisions of accelerated protons and surrounding gas or photons inside astrophysical sources produce high-energy neutrinos, the so called cosmic or astrophysical neutrinos. They are foretold to be connected to the most violent phenomena in the universe and reach the most extreme energies ever measured: the range of peta-electronvolt (*). Each year, just a handful of these high-energy cosmic neutrinos reach the Earth.

Whenever IceCube records a neutrino, it is difficult to tell where it originated – in the Earth's atmosphere or far away in the universe.

While back in 2013 IceCube has yielded evidence that such neutrinos do exist, no single responsible source could be identified yet. The mechanisms and the environments responsible for cosmic neutrinos are then still to be ascertained. There are many candidate sources, with Active Galactic Nuclei (AGN) among the most prominent. AGN are very massive black holes in centers of galaxies.

What are cosmic rays and what is multi-messenger astrophysics?

Discovered more than 100 years ago, cosmic rays remain today one of the most obscure phenomena in the universe. They are believed to be connected to the most violent phenomena observed, like Active Galactic Nuclei (AGN). These are galaxies emitting an enormous radiation outflow powered by the black holes at their centers. Scientists assume that part of this outflow is composed by the charged particles that we measure as cosmic rays. Some of those are likely to interact with matter or photons surrounding the black hole giving life to high energy neutrinos and also photons. Both are unaffected by the magnetic fields in our galaxy and in the intergalactic space, so they can propagate from their origin to us keeping memory of where they come from.

Electromagnetic observations help us to assess the possible association of a single neutrino to an astrophysical source. Combining information from different particles (and instruments) is what we call "multi-messenger astrophysics".

Furthermore, neutrinos and gamma-rays can tell us the story about the origin of cosmic rays. They give us different insights. The observation of one neutrino tells us that its source can accelerate protons and nuclei. Gamma-rays together with other electromagnetic signals give us a measure of the power emitted by the underlying engines as well as which are the leading particle interactions at work. By bringing together the messages of different particles – neutrinos and photons – we can achieve a deep understanding of what happens in the source and ultimately infer the story of cosmic rays.

What is MAGIC?

MAGIC is a system of two large telescopes that during dark nights collect light with two very large mirrors, each of them 17 meters in diameter. The telescopes are located on the Canary island of La Palma at an altitude of 2,200 meters. The MAGIC telescopes measure gamma-rays, or, more precisely, light produced by gamma-rays: Cherenkov radiation: This is produced after collisions of high energy photons with nuclei in the Earth's atmosphere. These collisions free a large number of charged particles which then emit the light observed by the MAGIC telescopes. From the pattern of this light we can reconstruct the direction and the energy of the mother photon. Of great interest are mother photons emitted in the most mysterious and energetic phenomena in the universe, for example the ones associated with the environment of supermassive black holes.

What about black holes?

Black holes are objects with a mass hundreds of million times the mass of the Sun. They host the most extreme environment for particles and their interactions. By studying such phenomena we verify our understanding of particle physics under conditions that we cannot explore with man made accelerators. It has long been believed that black holes can accelerate particles up to the most extreme energies and thus be the engines that power the cosmic rays that we observe on Earth. Evidence or this theory has been missing up to now.

What was observed?

A few years back IceCube had discovered neutrinos from the cosmos. However, they could not be traced back to a specific source. The underlying engine therefore was unknown. But we know that these neutrinos must be produced in extreme natural accelerators, where protons and atomic nuclei can reach energies far beyond those achieved in terrestrial man-made accelerators.

Several attempts were done in the past years to find the astrophysical sources of the high-energy neutrinos recorded by IceCube. Several suspects were claimed. None gave conclusive results.For the first time last fall, IceCube detected an energetic neutrino and could measure its direction with great precision. The rapid reaction from telescopes around the world on the ground and in space allowed astronomers to catch an energetic source shining in the sky. For the first time we have much more than just a few hints on what gives birth to these neutrinos.

The FERMI satellite detects gamma-rays of gigalectron (GeV) energies. Several thousand AGNs are known to emit GeV photons. Soon after the alert issued by IceCube the FERMI team announced that the known gamma-ray blazar TXS 0506+056, found in the neutrino sky area, was observed to be in an active state. FERMI continuously monitors the full sky, allowing to tell the probability for a chance coincidence of an active state of any blazar with any IceCube neutrino of similar properties. This was found to be one on a thousand, making the observation very suggestive. This leaves reduced room to doubts. But the story goes further beyond that.

The MAGIC telescopes could catch photons of very high energies coming from the neutrino direction. These are closest to the energy of the neutrino and therefore more directly connected to the responsible source. Soon after pointing their instruments, the MAGIC team reported detection of gamma-rays from TXS 0506+056 with energies up to 400 GeV. **This is the first-time observation of very high energy (VHE) gamma-rays from a source possibly connected to a cosmic neutrino, shaking the community further.**

This exceptional coincidence of a neutrino and gamma-rays supports for the first time a robust explanation for the origin of the neutrino and of the mother particles. The astrophysical source hosts a supermassive back hole ejecting collimated outflows of matter moving close to the light speed — the so-called relativistic jets.The observation of a high energy neutrino tells that its source can accelerate protons and ions. By combining this information with astronomical data, we get a more detailed picture of the mechanisms at works. The highest energy photons detected by MAGIC can tell us what is the power emitted by the engine and which are the maximum energies that proton and nuclei can reach in this natural accelerator. We see that indeed they reach those energies that we observe in the cosmic ray particles. For the first time we have strong hints that three cosmic messengers are connected by the same mechanism: the neutrinos, the gamma-rays and the cosmic rays.

What is the role of very highly energetic gamma-rays measured by MAGIC?
Based on the common assumptions on this class of sources, the conditions at work seem to be very unlikely to yield the observed neutrino with the given energy. At first glance the observed multi-messenger signals seem to be a chance coincidence seems a better explanation.

However, the MAGIC team shows that structures inside the jet are likely to provide the solution to this riddle and the messengers are truly connected by a common birth. Particles accelerated in the jet (protons and electrons) form a fast “spine" in the jet, moving at uppermost speed. The spine is surrounded by a slower “sheath” in which relativistic electrons emit photons, thanks to the existing magnetic field. Because of relativistic effects at work, the protons in the jet may collide with the less energetic sheath photons. This process is likely to yield the observed neutrino and the accompanying 400 GeV-photons measured by MAGIC.

If the neutrino was produced by such mechanism, the highest energy gamma-rays produced in the same interactions are expected to carry some memory of their common birth. The very same environment embracing the interacting protons is expected to retain some of the highest energy photons. Only those photons will be absorbed, carrying a characteristic energy which conforms to both the properties of the jets and the energy of the neutrino. If the model is correct, a clear signature is predicted.

MAGIC could indeed measure a distinctive loss in the population of such energetic gamma-rays, well matching the model prediction and all the observational data combined. This provides strong clues that interactions of protons are indeed at work in the jets of TXS 0506+056.

We are at the verge of a newly emerging field of observational high-energy neutrino and multi-messenger astronomy.

(*) 1 peta-electronvolt is 10^{15} electronvolt, corresponding to $3.82930210325 \times 10^{-8}$ kilocalories (kcal)