MULTI-MESSENGER ASTRONOMY

Cosmic hadron colliders

An ultrahigh-energy neutrino event detected with the IceCube detector in Antarctica, simultaneous and co-spatial with a multi-wavelength outburst of a blazar about 3 billion light years away, points unambiguously to lepto-hadronic cooling mechanisms in jetted active galactic nuclei.

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The Universe is pervaded by particles that travel close to the speed of light, so called cosmic rays. These can be low-mass (electrons and positrons, or leptons), but the majority are protons and heavy nuclei (hadrons), which can reach energies of ~10^{15} eV — and occasionally up to 10^{20} eV (the energy of a baseball travelling at 100 km h^{-1}) — and are thus called ultrahigh-energy cosmic rays (UHECRs). One century after their discovery, the sources and acceleration mechanisms of UHECRs still represent one of the biggest unsolved problems of astrophysics and astroparticle physics. Now, writing in *Nature Astronomy*, Shan Gao and collaborators[1] link the ultrahigh-energy (UHE) neutrino output of a blazar-type active galactic nucleus (a radio galaxy with its relativistic jet pointing only a few degrees away from the observer's line of sight) to its spectral energy distribution, and time variability of this output, through hadronic processes in the jet.

While cosmic rays at lower energies are probably accelerated in supernova remnants[2], UHECRs must have an extragalactic origin, because their gyration radius is larger than the size of the Milky Way for interstellar magnetic fields. The interaction of UHECRs with matter and optical/ultraviolet light initiates a photohadronic cascade accompanied by copious emission of very high-energy photons (>100 GeV) and UHE neutrinos[3]. This makes extragalactic jetted sources such as blazars and gamma-ray bursts the most plausible candidates as UHECR accelerators and UHE neutrino emitters (Fig. 1), owing to their huge energy densities (peak luminosities of ~10^{48} and ~10^{50} erg s^{-1}, respectively) and ultrarelativistic conditions (Lorentz factors of ~10 and ~100, respectively).

Neutrinos interact very weakly with matter. Unlike MeV neutrinos, which are produced in nuclear interactions occurring in stars and core-collapse supernova explosions[4–6], and whose detection is heavily affected by the atmospheric background,

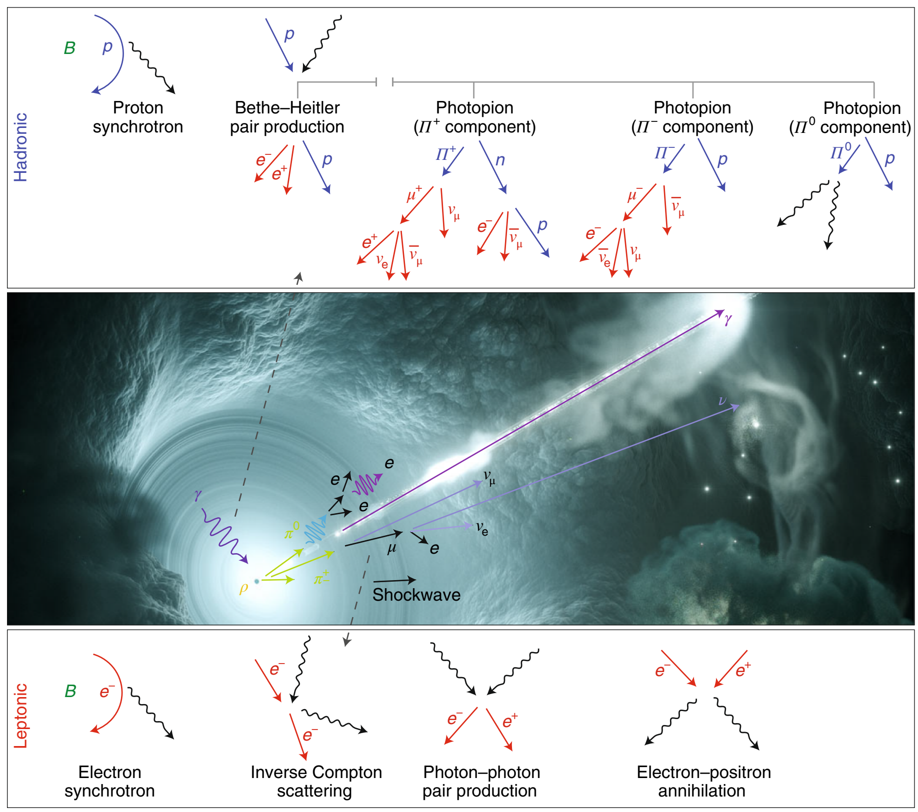

Fig. 1 | Artist impression of an active galactic nucleus producing highly energetic particles. The galactic nucleus is shown (not to scale) in the middle panel with a central supermassive black hole (not visible in this image) surrounded by an accretion disk (with a darkened outer rim) that powers a relativistic jet via extraction of rotational energy from the black hole. Highly energetic particles give rise to a number of processes and cascades of hadrons and leptons. The top and bottom panels show some of the scatterings that typically take place in the cascades. Top: a proton gyrating in a magnetic field loses energy via synchrotron radiation, and/or by impacting on the radiation field (indicated as a wiggled arrow), triggering the formation of electron–positron pairs or charged and neutral mesons (π and μ) that decay further into leptons, muons and neutrinos of various 'flavours'. Bottom: electrons cool via synchrotron radiation, and then up-scatter photons internal or external to the jet to higher energies (inverse Compton scattering). Gamma-ray photons of total energy larger than twice the electron rest-mass produce electron–positron pairs. The inverse process (pair annihilation into MeV photons) also occurs with comparable probability. Central image credit: DESY, Science Communication Lab.

UHE neutrinos are intrinsically very rare and suffer from a relatively low background. Therefore, UHE neutrinos are optimally chased using km-sized volumes of ice or water, where the upward-going muons they generate during their interaction with Earth rock leave traces in the form of Cherenkov optical light. This light can be collected with photomultipliers, measured and used to reconstruct the neutrino energy and direction of arrival in the sky with an accuracy of the order of several square degrees (depending on the muonic flux and fraction of detector volume crossed). Typical state-of-the-art UHE neutrino detectors, such as IceCube in Antarctica, and KM3NeT and ANTARES in the Mediterranean Sea, have these characteristics.

One such neutrino event, with an estimated energy of ~300 TeV, was detected by the IceCube detector on 22 September 2017[7]. The significance of the signal was estimated at the 56.5% level of confidence, based on the probability that a neutrino with the observed track energy and zenith angle was of astrophysical origin. The neutrino arrival direction is consistent with the location of the blazar TXS0506+056, at a redshift of $z = 0.33$ (ref. [8]), equivalent to a distance of 970 Mpc. The small viewing angle of a blazar jet axis and the very high plasma speeds within the jet relativistically boost the blazar jet luminosity by a factor of 100 to 1,000. In particular, this luminosity boost favours detection of the intrinsically rather low gamma-ray photon fluxes. The blazar TXS0506+056 underwent a flare at all frequencies up to the MeV–GeV range, as observed by the Fermi satellite, which coincided in time with the neutrino detection. A flare at very high energies (>90 GeV) was detected starting two weeks later with the ground-based atmospheric Cherenkov telescope MAGIC[7]. The very high energy tail of the blazar spectrum and the simultaneity of the multi-wavelength and UHE neutrino outbursts represent a strong case for their association, and thus offer a potential solution to the longstanding issue of the acceleration of UHECRs. A previous claimed association between a blazar flare and a PeV-energy neutrino detection was equally tantalizing but not regarded as similarly significant because of a lower probability of temporal and angular coincidence[9,10]. It is generally accepted that blazar spectra up to the soft X-ray range are produced by relativistic electrons radiating via the synchrotron process. However, at the higher energies (up to the maximum observable electromagnetic frequencies — that is, ~10^{25} Hz) two emission models compete[3]: in a fully leptonic regime, the higher energy spectrum is due to inverse Compton scattering of relativistic electrons off jet photons or external radiation fields; alternatively, a lepto-hadronic model scenario also envisages the cooling of pions and muons in a hadronic cascade, producing high-energy photons. Protons or nucleons accelerated in relativistic jets to very high energies by the Fermi diffusive shock acceleration mechanism initiate cascades of neutral and charged mesons that in turn decay into other particles, UHE neutrinos and gamma-rays. UHE neutrino detection from blazar sources is therefore regarded as the signature of hadronic processes in their jets. Some of these accelerated hadrons manifest as cosmic rays when freely travelling through space to the Earth.

Gao et al. show that a hadronic interpretation of the spectrum of TXS0506+056 is not viable, because X-rays would be over-produced, while a fully leptonic one is satisfactory. Since a hadronic contribution is, however, unavoidable if the IceCube-detected neutrino is associated with the blazar, it must be sub-dominant with respect to the leptonic one, so that no X-ray flux excess is predicted. They adopt a time-dependent code that reproduces the blazar multi-wavelength light curves and the neutrino flux as a function of time. Specifically, they have endeavoured to establish the minimum fraction of hadronic-produced electromagnetic spectral flux that is necessary to explain the observed neutrinos without contradicting the multi-wavelength observations. The neutrino time behaviour is correlated with that at hard X-rays and ~0.1 TeV energies, but not with that at MeV–GeV energies, indicating that hard X-ray and very high energy photons are produced by hadronic processes, while optical, soft X-ray and MeV–GeV photons have a leptonic origin. As a consequence, the very high energy outburst is expected to be delayed with respect to the MeV–GeV one, as observed by MAGIC and Fermi LAT[7], because nucleons lose energy more slowly than leptons. In systematically vetting models for blazar emission, Gao et al. provide an observation-motivated interpretative picture for blazars as UHECR accelerators, thus addressing a century-long conundrum, besides planting one more flag on the discovery pathway of multi-messenger astrophysics. As often happens when idealized schemes are applied to actual physical engines, several hurdles plague a fully self-consistent and acceptable theoretical description, partly because the multi-wavelength data are sparse and not exactly simultaneous. Gao et al. critically analyse the models in view of the biggest problems (for example, the imperfect match between observed and predicted neutrino luminosity, and the very high total energy requirements) and, in realizing the possible degeneracy of model parameters, provide a word of caution about possible multiple coexisting mechanisms.

Future correlated observations with UHE neutrino experiments and multi-wavelength electromagnetic facilities — as well as intensive monitoring, especially in the gamma-ray range, and notably with the sensitive future Cherenkov Telescope Array — will be crucial to clarify the precise interplay of leptonic and hadronic components in plasma composition that leads to UHE neutrino production in blazars and possibly in gamma-ray bursts. ❐

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Published online: 05 November 2018
https://doi.org/10.1038/s41550-018-0613-y

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