Ultra-high-energy cosmic ray

In astroparticle physics, an ultra-high-energy cosmic ray (UHECR) is a cosmic ray particle with a kinetic energy greater than $10^{18}$ eV, far beyond both its rest mass and energies typical of other cosmic ray particles.

An extreme-energy cosmic ray (EECR) is an UHECR with energy exceeding $5 \times 10^{19}$ eV (about 8 Joule), the so-called Greisen–Zatsepin–Kuzmin limit (GZK limit).

These particles are extremely rare, the total number of observed events between 1962 and the completion of Pierre Auger Observatory (PAO) in 2008 ranging at a few dozen at the most. The PAO is designed to survey an area of some 3000 km$^2$ and expects to see maybe one such particle every one or two weeks. During the phasing in of its operation during 2004 to 2007, a total number of 27 events with estimated arrival energies above $5.7 \times 10^{19}$ eV were reported. Ultra-high-energy particles are significant for astrophysics and fundamental physics theory, because they have energies comparable to the GZK limit, which occurs at about $5 \times 10^{19}$ eV. This limit should be the maximum energy of cosmic ray particles that have traveled long distances (about 160 million light years), due to the theoretical energy losses of higher-energy ray particles and to scattering from photons in the cosmic microwave background. It follows that EECR could not be surviving from the early universe but are cosmologically "young", emitted somewhere in the Local Supercluster by some unknown physical process.

The postulated (hypothetical) sources of EECR are known as Zevatrons, named in analogy to Lawrence Berkeley National Laboratory's Bevatron and Fermilab's Tevatron, and therefore capable of accelerating particles to 1 ZeV ($10^{21}$ eV). In 2004 there was a consideration of the possibility of galactic jets acting as Zevatrons, due to diffusive acceleration of particles caused by shock waves inside the jets. In particular, models suggested that shock waves from the nearby M87 galactic jet could accelerate an iron nucleus to ZeV ranges. In 2007, PAO tentatively associated EECR with extragalactic supermassive black holes at the center of nearby galaxies called active galactic nuclei (AGN). A more speculative suggestion Grib and Pavlov (2007, 2008) envisages the decay of superheavy dark matter by means of the Penrose process.

Observational history

The first observation of a cosmic ray particle with an energy exceeding $1.0 \times 10^{20}$ eV (16 J) was made by Dr John D Linsley and Livio Scarsi at the Volcano Ranch experiment in New Mexico in 1962. Cosmic ray particles with even higher energies have since been observed. Among them was the Oh-My-God particle observed on the evening of 15 October 1991 over Dugway Proving Ground, Utah. Its observation was a shock to astrophysicists, who estimated its energy to be approximately $3 \times 10^{20}$ eV (50 J)—in other words, a subatomic particle with kinetic energy equal to that of a baseball (5 ounces or 142 grams) traveling at about 100 kilometers per hour (60 mph). It was most likely a proton traveling very close to the speed of light, slower by only about 1.5 femtometers per second, or at about $0.9999999999999999999999951 c$, based on its observed energy. At that speed, in a year-long race between light and the particle, the particle would fall behind only 46 nanometers, or 0.15 femtoseconds ($1.5 \times 10^{-16}$ s).

The energy of this particle is some 40 million times that of the highest energy protons that have been produced in any terrestrial particle accelerator. However, only a small fraction of this energy would be available for an interaction with a proton or neutron on Earth, with most of the energy remaining in the form of kinetic energy of the products of the interaction. The effective energy available for such a collision is the square root of double the product of the particle's energy and the mass energy of the proton, which for this particle gives $7.5 \times 10^{14}$ eV, roughly 50 times the collision energy of the Large Hadron Collider.

Since the first observation, by the University of Utah's Fly's Eye Cosmic Ray Detector, at least fifteen similar events have been recorded, confirming the phenomenon. These very high energy cosmic ray particles are very rare; the energy of most cosmic ray particles is between 10 MeV and 10 GeV.
Ultra-high-energy cosmic ray observatories

- AGASA – Akeno Giant Air Shower Array in Japan
- Antarctic Impulse Transient Antenna (ANITA) detects ultra-high-energy cosmic neutrinos believed to be caused by ultra-high-energy cosmic ray particles
- Extreme Universe Space Observatory
- GRAPES-3 (Gamma Ray Astronomy PeV EnergieS 3rd establishment) is a project for cosmic ray study with air shower detector array and large area muon detectors at Ooty in southern India.
- High Resolution Fly's Eye Cosmic Ray Detector (HiRes)
- LOPES (telescope) – LOFAR PrototypE Station is located in Karlsruhe, Germany is part of the LOFAR project.
- MARIACHI – Mixed Apparatus for Radar Investigation of Cosmic-rays of High Ionization located on Long Island, USA.
- Pierre Auger Observatory
- Telescope Array Project
- Yakutsk Extensive Air Shower Array
- The COSMICi project at FAMU is developing technology for a distributed network of low-cost detectors for UHECR showers in collaboration with MARIACHI.

Pierre Auger Observatory

Pierre Auger Observatory is an international cosmic ray observatory designed to detect ultra-high-energy cosmic ray particles (with energies beyond $10^{20}$ eV). These high-energy particles have an estimated arrival rate of just 1 per square kilometer per century, therefore, in order to record a large number of these events, the Auger Observatory has created a detection area of 3,000 km² (the size of Rhode Island, USA) in Mendoza Province, western Argentina. A larger cosmic-ray detector array is also planned for the northern hemisphere as part of the Pierre Auger complex. The Pierre Auger Observatory, in addition to obtaining directional information from the cluster of water tanks used to observe the cosmic-ray-shower components, also has four telescopes trained on the night sky to observe fluorescence of the nitrogen molecules as the shower particles traverse the sky, giving further directional information on the original cosmic ray particle.

Suggested explanations

Neutron Stars accelerating particles to UHECR energies

One suggested source of UHECR particles is their origination from neutron stars. In young neutron stars with spin periods of <10ms, the magnetohydrodynamic (MHD) forces from the quasi-neutral fluid of superconducting protons and electrons existing in a neutron superfluid accelerate iron nuclei to UHECR velocities. The magnetic field produced by the neutron superfluid in rapidly-rotating stars creates a magnetic field of $10^8$–$10^{11}$ tesla, at which point the neutron star is classified as a magnetar. This magnetic field is the strongest in the observed universe and creates the relativistic MHD wind believed to accelerate iron nuclei remaining from the supernova to the necessary energy.

Another hypothesized source of UHECRs from neutron stars is during neutron star to strange star combustion. This hypothesis relies on the assumption that strange matter is the ground state of matter which has no experimental or observational data to support it. Due to the immense gravitational pressures from the neutron star, it is believed that small pockets of matter consisting of up, down, and strange quarks in equilibrium acting as a single hadron (as opposed to a number of $\Sigma^0$ baryons). This will then combust the entire star to strange matter, at which point the neutron star becomes a strange star and its magnetic field breaks down, which occurs because the protons and neutrons in the quasi-neutral fluid have become strangelets. This magnetic field breakdown releases large amplitude electromagnetic waves (LAEMWs). The LAEMWs accelerate light ion remnants from the supernova to UHECR energies.
Ultra-high-energy cosmic ray particles have been a mystery for many years. Recent results from the Pierre Auger Observatory show that ultra-high-energy cosmic ray arrival directions appear to be correlated with extragalactic supermassive black holes at the center of nearby galaxies called active galactic nuclei (AGN). However, since the angular correlation scale used is fairly large (3.1 degrees) these results do not unambiguously identify the origins of such cosmic ray particles. The AGN could merely be closely associated with the actual sources, for example in galaxies or other astrophysical objects that are clumped with matter on large scales within 100 Mpc.\[citation needed\]

Some of the supermassive black holes in AGN are known to be rotating, as in the Seyfert galaxy MCG 6-30-15 with time-variability in their inner accretion disks. Black hole spin is a potentially effective agent to drive UHECR production, provided ions are suitably launched to circumvent limiting factors deep within the nucleus, notably curvature radiation and inelastic scattering with radiation from the inner disk. Low-luminosity, intermittent Seyfert galaxies may meet the formation of a linear accelerator several light years away from the nucleus, yet within their extended ion tori whose UV radiation ensures a supply of ionic contaminants. The corresponding electric fields are small, on the order of 10 V/cm, whereby the observed UHECRs are indicative for the astronomical size of the source. Improved statistics by the Pierre Auger Observatory will be instrumental in identifying the presently tentative association of UHECRs (from the Local Universe) with Seyferts and LINERs.[4]

Other possible sources of the particles

Other possible sources of the UHECR are:[5]

- radio lobes of powerful radio galaxies
- intergalactic shocks created during the epoch of galaxy formation
- hypernovae
- relativistic supernovae
- gamma-ray bursts
- decay products of supermassive particles from topological defects, left over from phase transitions in the early universe
- Particles undergoing the Penrose effect.

Relation with dark matter

It is hypothesized that active galactic nuclei are capable of converting dark matter into high energy protons. Yuri Pavlov and Andrey Grib at the Alexander Friedmann Laboratory for Theoretical Physics at St. Petersburg hypothesize that dark matter particles are about 15 times heavier than protons, and that they can decay into pairs of particles of a type that interacts with ordinary matter.[6] Near an active galactic nucleus, one of these particles can fall into the black hole, while the other escapes, as described by the Penrose process. Some of the particles that escape will collide with incoming particles creating collisions of very high energy. It is in these collisions, according to Pavlov, that ordinary visible protons can form. These protons would have very high energies. Pavlov claims that evidence of this is present in the form of ultra-high-energy cosmic ray particles.[7] Ultra-high energy cosmic ray particles may also be produced by the decay of super-heavy dark matter "X particles"[8] such as Holeums.[9] Such very energetic decay products, carrying a fraction of the mass of the X particle, are believed to be a plausible explanation for the observed ultra-high energy cosmic rays (UHECR).

High energy cosmic ray particles traversing intergalactic space suffer the GZK cutoff above $10^{20} \text{ eV}$ due to interactions with cosmic background radiation if the primary cosmic ray particles are protons or nuclei. The Pierre Auger Project, HiRes and Yakutsk Extensive Air Shower Array found the GZK cutoff, while Akeno-AGASA
observed the events above the cutoff (11 events in the past 10 years). The result of the Akeno-AGASA experiment is smooth near the GZK cutoff energy. If one assumes that the Akeno-AGASA result is correct and consider its implication, a possible explanation for the AGASA data on GZK cutoff violation would be a shower caused by dark matter particles. A dark matter particle is not constrained by the GZK cutoff, since it interacts weakly with cosmic background radiation. Recent measurements by the Pierre Auger Project have found a correlation between the direction of high energy cosmic ray particles and the location of AGN.\[10\]

References


Further reading


External links

- The Highest Energy Particle Ever Recorded (http://www.cosmic-ray.org/reading/flyseye.html#SEC10) The details of the event from the official site of the Fly's Eye detector.
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