Greisen–Zatsepin–Kuzmin limit

The Greisen–Zatsepin–Kuzmin limit (GZK limit) is a theoretical upper limit on the energy of cosmic rays (high energy charged particles from space) coming from "distant" sources. The limit is $5 \times 10^{19}$ eV, or about 8 joules. The limit is set by slowing-interactions of cosmic ray protons with the microwave background radiation over long distances (~163 million light-years). The limit is at the same order of magnitude as the upper limit for energy at which cosmic rays have experimentally been detected. For example, one ultra-high-energy cosmic ray has been detected which appeared to possess a record 50 joules (312 million TeV) of energy (about the same as the kinetic energy of a 60 mph baseball).

Cosmologists and theoretical physicists have regarded such observations as key in the search for explorations of physics in the energy realms which would require new theories of quantum gravity and other theories which predict events at the Planck scale. This is because protons at these extreme energies (3 million TeV) are much closer to the Planck energy (about 2 billion joules, or $1.22 \times 10^{16}$ TeV) than any particles that can be made by current particle accelerators (20 TeV, or 3 millionths of a joule). They are thus suitable as a probe into realms where the theory of special relativity breaks down. Physicist Lee Smolin has written that if such cosmic rays which violate the GZK limit can be confirmed, and other possible explanations discounted, it "would be the most momentous discovery of the last hundred years—the first breakdown of the basic theories comprising the twentieth century's scientific revolution."[1]

Computation of the GZK-limit

The limit was independently computed in 1966 by Kenneth Greisen, Vadim Kuzmin, and Georgiy Zatsepin based on interactions between cosmic rays and the photons of the cosmic microwave background radiation (CMB). They predicted that cosmic rays with energies over the threshold energy of $5 \times 10^{19}$ eV would interact with cosmic microwave background photons $\gamma_{\text{CMB}}$, relatively blueshifted by the speed of the cosmic rays, to produce pions via the $\Delta$ resonance,

$$\gamma_{\text{CMB}} + p \rightarrow \Delta^+ \rightarrow p + \pi^0;$$

or

$$\gamma_{\text{CMB}} + p \rightarrow \Delta^+ \rightarrow n + \pi^+. $$

Pions produced in this manner proceed to decay in the standard pion channels—ultimately to photons for neutral pions, and photons, positrons, and various neutrinos for positive pions. Neutrons decay also to similar products, so that ultimately the energy of any cosmic ray proton is drained off by production of high energy photons plus (in some cases) high energy electron/positron pairs and neutrino pairs.

The pion production process begins at a higher energy than ordinary electron-positron pair production (lepton production) from protons impacting the CMB, which starts at cosmic ray proton energies of only about $10^{17}$ eV. However, pion production events drain 20% of the energy of a cosmic ray proton as compared with only 0.1% of its energy for electron positron pair production. This factor of 200 is from two sources: the pion has only about ~130 times the mass of the leptons, but the extra energy appears as different kinetic energies of the pion or leptons, and results in relatively more kinetic energy transferred to a heavier product pion, in order to conserve momentum. The much larger total energy losses from pion production result in the pion production process becoming the limiting one to high energy cosmic ray travel, rather than the lower-energy light-lepton production process.

The pion production process continues until the cosmic ray energy falls below the pion production threshold. Due to the mean path associated with this interaction, extragalactic cosmic rays traveling over distances larger than 50 Mpc (163 Mly) and with energies greater than this threshold should never be observed on Earth. This distance is also known as GZK horizon.
Cosmic ray paradox

Why is it that some cosmic rays appear to possess energies that are theoretically too high, given that there are no possible near-Earth sources, and that rays from distant sources should have scattered off the cosmic microwave background radiation?

A number of observations have been made by the AGASA experiment that appeared to show cosmic rays from distant sources with energies above this limit (called ultra-high-energy cosmic rays, or UHECRs). The observed existence of these particles was the so-called GZK paradox or cosmic ray paradox.

These observations appear to contradict the predictions of special relativity and particle physics as they are presently understood. However, there are a number of possible explanations for these observations that may resolve this inconsistency.

• The observations could be due to an instrument error or an incorrect interpretation of the experiment, especially wrong energy assignment.
• The cosmic rays could have local sources well within the GZK horizon (although it is unclear what these sources could be).
• Heavier nuclei could possibly circumvent the GZK limit.

Weakly interacting particles

Another suggestion involves ultra-high energy weakly interacting particles (for instance, neutrinos) which might be created at great distances and later react locally to give rise to the particles observed. In the proposed Z-burst model, an ultra-high cosmic neutrino collides with a relic anti-neutrino in our galaxy and annihilates to hadrons. This process proceeds via a (virtual) Z-boson:

\[ \nu + \bar{\nu} \rightarrow Z \rightarrow \text{hadrons} \]

The cross section for this process becomes large if the center of mass energy of the neutrino antineutrino pair is equal to the Z-boson mass (such a peak in the cross section is called "resonance"). Assuming that the relic anti-neutrino is at rest, the energy of the incident cosmic neutrino has to be:

\[ E = \frac{m_Z^2}{2m_\nu} = 4.2 \times 10^{21} \left( \frac{\text{eV}}{m_\nu} \right) \text{ eV} \]

where \( m_Z \) is the mass of the Z-boson and \( m_\nu \), the mass of the neutrino.

Proposed theories for particles above the GZK-cutoff

A number of exotic theories have been advanced to explain the AGASA observations, including doubly special relativity. However, it is now established that standard doubly special relativity does not predict any GZK suppression (or GZK cutoff), contrary to models of Lorentz symmetry violation involving an absolute rest frame.[2]

Other possible theories involve a relation with dark matter, decays of exotic super-heavy particles beyond those known in the Standard Model.

Conflicting evidence for GZK-cutoff

In July 2007, during the 30th International Cosmic Ray Conference in Mérida, Yucatán, México, the High Resolution Fly’s Eye Experiment (HiRes) and the Auger International Collaboration presented their results on ultra-high-energy cosmic rays. HiRes has observed a suppression in the UHECR spectrum at just the right energy, observing only 13 events with an energy above the threshold, while expecting 43 with no suppression. This result has been published in the Physical Review Letters in 2008 and as such is the first observation of the GZK Suppression.[1] The Auger Observatory has confirmed this result.[1] instead of the 30 events necessary to confirm the AGASA results, Auger saw only two, which are believed to be heavy nuclei events. According to Alan Watson,
spokesperson for the Auger Collaboration, AGASA results have been shown to be incorrect, possibly due to the systematical shift in energy assignment.

**Extreme Universe Space Observatory on Japanese Experiment Module (JEM-EUSO)**

EUSO which was scheduled to fly on the International Space Station (ISS) in 2009, was designed to use the atmospheric-fluorescence technique to monitor a huge area and boost the statistics of UHECRs considerably. EUSO is to make a deep survey of UHECR-induced extensive air showers (EASs) from space, extending the measured energy spectrum well beyond the GZK-cutoff. It is to search for the origin of UHECRs, determine the nature of the origin of UHECRs, make an all-sky survey of the arrival direction of UHECRs, and seek to open the astronomical window on the extreme-energy universe with neutrinos. The fate of the EUSO Observatory is still unclear since NASA is considering early retirement of the ISS.

**The Fermi Gamma-ray Space Telescope to resolve inconsistencies**

Launched in June 2008, the Fermi Gamma-ray Space Telescope (formerly GLAST) will also provide data that will help resolve these inconsistencies.

- With the Fermi Gamma-ray Space Telescope, one has the possibility of detecting gamma rays from the freshly accelerated cosmic-ray nuclei at their acceleration site (the source of the UHECRs).[3]
- UHECR protons accelerated in astrophysical objects produce *secondary electromagnetic cascades* during propagation in the cosmic microwave and infrared backgrounds, of which the GZK-process of pion production is one of the contributors. Such cascades can contribute between $\approx 1\%$ and $\approx 50\%$ of the GeV-TeV diffuse photon flux measured by the EGRET experiment. The Fermi Gamma-ray Space Telescope may discover this flux.[1]

**Possible sources of UHECRs**

In November 2007, researchers at the Pierre Auger Observatory announced that they had evidence that UHECRs appear to come from the active galactic nuclei (AGNs) of energetic galaxies powered by matter swirling onto a supermassive black hole. The cosmic rays were detected and traced back to the AGNs using the Véron-Cetty-Véron catalog. These results are reported in the journal *Science*.[4] Nevertheless, the strength of the correlation with AGNs from this particular catalog for the Auger data recorded after 2007 has been slowly diminishing.[5]

**Pierre Auger Observatory results on UHECRs above GZK-limit**

According to the analysis made by the AUGER collaboration, the existence of the GZK cutoff may have been confirmed, but important uncertainties remain in the interpretation of the experimental results and further work is required.[6]

In 2010 final results of The High Resolution Fly's Eye (HiRes) experiment reconfirmed earlier results of the GZK cutoff from the HiRes experiment.[7] The results were previously brought into question when the AGASA experiment hinted at suppression of the GZK cutoff in their spectrum. The AUGER collaboration results agree with some parts of the HiRes final results on the GZK cutoff, but some discrepancies still remain.
References


External links

- Rutgers University experimental high energy physics HIRES research page ([http://www.physics.rutgers.edu/hex/HURES.html](http://www.physics.rutgers.edu/hex/HURES.html))
- Pierre Auger Observatory page ([http://www.auger.org](http://www.auger.org))
- "Could the end be in sight for ultrahigh-energy cosmic rays?" ([http://physicsweb.org/article/world/15/9/3](http://physicsweb.org/article/world/15/9/3)), Subir Sarkar, PhysicsWeb, 2002

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