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Could quark stars be a source of ultra high energy cosmic rays

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Abstract

The origin of cosmic rays with ultra-high energies (UHE) remains mystery.In our paper*, we have discussed whether dense quark matter – quark-gluon plasma, formed in the centers of neutron stars or Quark Stars (QS), could be a source of these UHE cosmic rays. QS, in particular, are more likely candidates for being the source of UHE cosmic rays, although for a long time, they remained unobserved. A recent study** proposed that the low-mass companion of the black hole in GW190814 might be a strange quark star. In the talk we continue to discuss that the QS's matter, could be a source of the UHE particles. Results from the RHIC and LHC experiments on ultrarelativistic heavy ion collisions suggest that the quark-gluon matter produced in such collisions displaying collective behavior. This behavior could lead to the formation of a coherent group of partons (CGP). A collision between a parton and the CGP, similar to a photon colliding with a high-energy electron, could result in the parton gaining energy through the inverse Compton effect, thereby accelerating without an external field.

Keywords: cosmic rays; ultra-high energies; quark-gluon plasma; Quark Stars; ultrarelativistic; heavy ion collisions.
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1. Introduction

Cosmic particles (CRs) are vital carriers of information about the creation and evolution of the Universe. They were discovered in 1912 by Victor Hess, he observed "penetrating radiation" from space. CRs are highly energetic charged particles. Melvin Burt Gottlieb and Van Allen showed (in 1948) that these particles are

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mainly protons, a few helium and heavier nuclei. They strike Earth from all directions and create a constant radiation background. Actually, this means that a lot of cosmic ray particles pass through man bodies every minute, but the resulting radiation imprint is relatively low if we compare this to the natural background radiation.

In 1938, French physicist Pierre Auger [1] discovered a remarkable phenomenon – showers of secondary cosmic particles that arise as a result of the interaction of primary protons and nuclei of extremely high energies with the nuclei of atmospheric atoms. It turned out that in the spectrum of cosmic rays there are particles with an energy of the order of 10^{15}-10^{18} eV – millions of times more energy than the particles accelerated in the laboratory.

The discovery of very high-energy cosmic particles immediately raised the question: what is the mechanism for accelerating charged particles in astrophysical objects? The answer turned out to be non-trivial: a natural, “cosmic” accelerator is radically different from man-made accelerators.

The first mechanism of cosmic ray acceleration was proposed by Enrico Fermi [2] for protons chaotically colliding with magnetized clouds of interstellar plasma, but could not explain all the experimental data.

The Fig. 1 shows the spectrum of CRs [3]. The figure shows sources of cosmic rays too.

In 1977, G. F. Krymsky showed [4] that acceleration of cosmic particles could be done by shock wave. This mechanism should accelerate particles in supernova remnants much more strongly at the fronts of shock waves, the speeds of which are orders of magnitude higher than the speeds of the clouds. Today it has been reliably shown that the mechanism of acceleration of cosmic protons and nuclei by a shock wave in the shells of Supernovae is most effective. But it is unlikely to be able to reproduce it in laboratory conditions: acceleration occurs relatively slowly and requires enormous amounts of energy to retain accelerated particles. In supernova, these conditions exist due to the very nature of the explosion. It is remarkable that the acceleration of cosmic rays occurs in a unique astrophysical object, which is responsible for the synthesis of heavy nuclei (heavier than helium) actually present in cosmic rays.

One can say that the idea of cosmic rays as a “local” galactic phenomenon turned out to be true only for particles of moderate energies $E < 10^{17}$ eV that has been convincingly demonstrated in experiments measuring the energy spectrum of cosmic rays.

On 25 of November 2023 it was announced that a team of scientists from the Telescope Array project recorded the second most powerful cosmic ray in the history of observations [5]. This was reported at the University of Utah (USA). Scientists call cosmic rays the charged particles that come from sources inside and outside the Milky Way. The energy of the beam, which was recorded by the Telescope

Array, is approximately equal to 2.4 x 10^{20} eV. Astrophysicists explain that nothing in our galaxy could produce such a stream of particles. In addition, their energy was more powerful than was thought possible for cosmic rays.

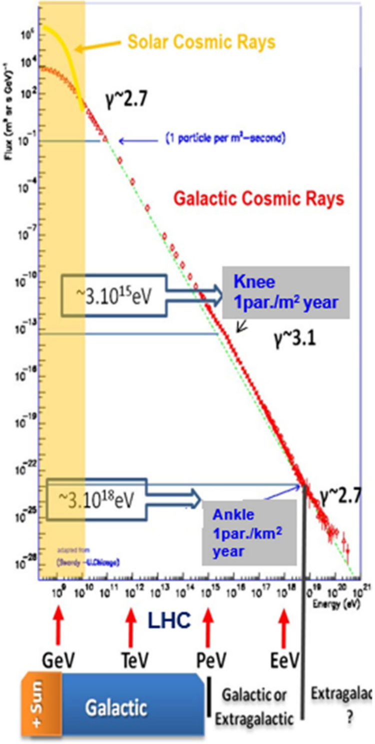

Fig. 1. The spectrum of CRs, denoting the different components and sources (Credit: A. Papaioannou, adopted from the CR spectrum by S. Swordy).

2. Explanation

In the papers [6] we have discussed a possible source of ultra-high energy cosmic rays, without acceleration in an electromagnetic field. We proposed that the dense quark-gluon matter could be a source of the ultra-high-energy particles. We therefore think so that experimental results on ultrarelativistic heavy ion collisions coming from RHIC and LHC point out the collective behavior of the partons in the dence quark- gluon matter - Quark Gluon Plasma (QGP). We think that the collective behavior of the partons could lead to formation of the higher energy objects - coherent parton group (Fig.2). Partons could collide with this group (Fig.2), and as in the case of a collision of a photon with a higher energy electron, the parton can gain energy, accelerate transiting into higher p_T region (inverse Compton effect, Fig.3) of the secondary particles p_T spectra. After a significant energy loss, the coherent parton group can decay into partons with lower energies – the slowed partons which will be in the interval of lower p_T region.

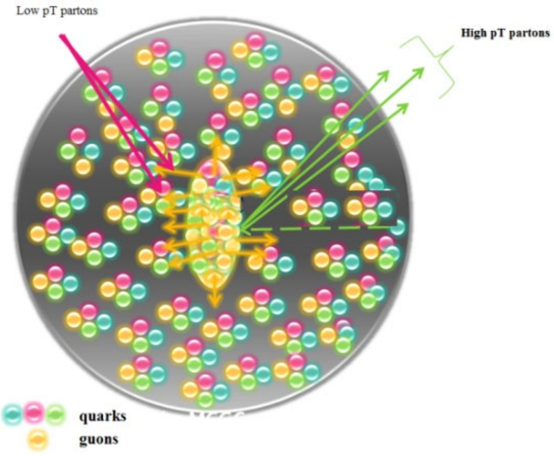

Fig. 2

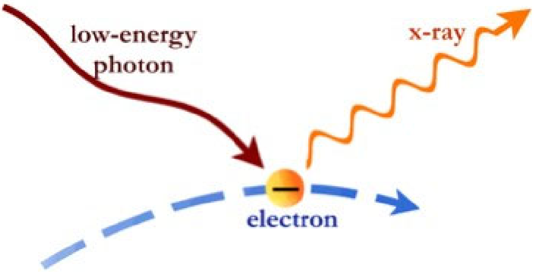

Fig. 3

As a result of the transitions of slowed and accelerate partons from the region of high probable parton formation, it can be seen that the jets were suppressed. It can influence on the jet quenching effect [7] and makes them stronger in this region. Let us note that the jet quenching effect is the most important signature for the formation of the QGP in Heavy Ion Collisions at ultrarelativistic energies [8] and it is caused by energy loss of jet partons (via collisional and radiative interactions) from early hard scattering with a hot and dense medium before fragmenting into hadrons.

To quantitative characterize the jet quenching effect the Nuclear Modification factor are used:

$$R_{AA} = \frac{d^2N/dp_T d\eta}{< T_{AA} > d^2\sigma^{NN}/dp_T d\eta}.$$

In *AA*-collisions, the nuclear overlap function is defined as:

$$< T_{AA} > = < N_{coll} > /\sigma_{inel}^{NN}$$

where $< N_{coll} >$ and σ_{inel}^{NN} represent the average number of binary nucleon-nucleon collisions in *AA* interactions and the inelastic cross-section in *NN* collisions, respectively. It is determined from the Glauber model. In the absence of nuclear effects, the AA is expected to be equal to unity. The behavior of the R_{AA} as a function of p_T for the charged particles produced in the most central *Pb-Pb* collisions at 2.76 A TeV [9]; several trends observed as p_T increases:

– increasing from ~ 0.36 to ~ 0.42 at $p_T < 2$ GeV/c;

– decreases to ~ 0.15 and reaches its minimum at $2 < p_T < 7$ GeV/c;

– increasing from ~ 0.15 to ~0.6 and reaches its maximum at $7 < p_T < 40$-50 GeV/c;

– *at* $p_T \cong$ 50-60 GeV/c, a regime change occurs and the values of R_{AA} remain at 0.6.

In the paper [10] that was shown the behavior of R_{AA} in the interval $7 < p_T < 100$ GeV/c is similar to the behavior of the photon energy distribution under ICE. A reason for this similarity may be that in the momentum interval $5 < p_T < 10$ GeV/c partons collide with higher energy objects, and as in the case of a collision of a photon with a higher energy electron, parton ICE occurs.

3. Conclusion

In the talk we discuss that the Quark Stars, could be a source of the ultra high energy cosmic particles. This becomes relevant because on 25 of November 2023 it was announced that a team of scientists from the Telescope Array project recorded the second most powerful cosmic ray in the history of observations. The energy of the beam, which was recorded by the Telescope Array, is approximately equal to 2.4×10^{20} eV. Astrophysicists explain that nothing in our galaxy could produce such a stream of particles. We try to show that dense strange quark matter formed in the Quark Stars, could generated the ultra-high energy cosmic particles. We therefore think so that the experimental results coming from the ultrarelativistic heavy ion collisions from RHIC and LHC demonstrated to exist of a collective behavior for the partons in the dence quark- gluon matter. This effect could lead to formation coherent group of partons. The mass and energy of the group must be essentially greater that the energy of a parton (with out group). The lasts could collide with this the grouped partons and gain energy, accelerate (effect likes the inverse Compton effect for photons, thereby accelerating without an external field).

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