Looking for the Gluon Condensation Signature in Protons Using the Earth-limb Gamma-Ray Spectra

Lei Feng\(^1\), Jianhong Ruan\(^1\), Fan Wang\(^3\), and Wei Zhu\(^1\)

\(^1\)Department of Physics, East China Normal University, Shanghai 200241, People’s Republic of China; wzhu@phy.ecnu.edu.cn
\(^2\)Key Laboratory of Dark Matter and Space Astronomy, Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210008, People’s Republic of China
\(^3\)Department of Physics, Nanjing University, Nanjing,210093, People’s Republic of China

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Abstract

A new type of gamma-ray spectrum is predicted in a general hadronic framework by taking into account gluon condensation (GC) effects in proton. The result presents a power law with a sharp break in the gamma-ray spectra at the TeV band. We suggest probing this GC signature in Earth-limb gamma-ray spectra using the Dark Matter Particle Explorer and the Calorimetric Electron Telescope in orbit.

Key words: astroparticle physics – atmospheric effects – chaos – elementary particles – gamma rays: general

1. Introduction

A quantum chromodynamics (QCD) study predicts that gluons in protons may converge to a critical momentum \((x_c, k_c)\) (Figure 1), where \(x\) is the fraction of longitudinal momentum and \(k\) is the transverse momentum carried by gluons (Zhu et al. 2008, 2016; Zhu & Lan 2017). This is gluon condensation (GC). GC should induce significant effects in proton collision processes, provided the collision energy is higher than the GC threshold \(E_{p-p(A)}^{GC}\).

The energy of protons accelerated inside some sources, such as supernova remnants (SNRs), active galactic nuclei (AGNs), or pulsars, could reach a very high level. Observations of such galactic diffuse emission (GDE) have provided valuable information about cosmic rays. The power law is the general form of cosmic-ray spectra at high energy. It is described by a straight energy spectrum line with a fixed index in log–log representation. This line may span over one order of magnitude. The power law has a QCD explanation (Wong et al. 2015). On the other hand, a break in the power law has also been observed and discussed in many works (Yalcin et al. 2018). The broken power law is related to extra sources of cosmic rays or even a new effect. Relativistic protons with energy exceeding \(E_{p-p(A)}^{GC}\) collide with protons or nuclei, and produce a vast number of photons through \(p + p(A) \rightarrow \pi^0 \rightarrow 2\gamma\). One can imagine that these excess photons break the smooth \(\gamma\)-ray background at the break energy \(E_{\gamma}^B\).

In this report, we try to find an effective way to identify the GC signature in cosmic \(\gamma\)-rays. We noticed that there are different gamma-radiation mechanisms. Usually, even one \(\gamma\)-ray spectrum can lead to a debate of whether it can be explained by a leptonic or hadronic framework. Therefore, we ask, what does the spectrum with a GC characteristic look like? Can it distinguish GC effects from other phenomena? For this reason, we give a brief overview of GC effects in Section 2. Then, we study the GC effects in a general hadronic framework in Section 3. We derived an analytic solution of \(\gamma\)-ray spectra with GC effects. The results present clearly a sharply broken power law, which is different from other, smooth, \(\gamma\)-ray spectra.

However, a series of uncertainties in hadronic processes may hinder our judgement of the GC signature. (i) We cannot be sure of the acceleration mechanism and the primary proton spectra in different environments. (ii) What is the target nucleus and its abundance? (iii) The complex interactions of photons with the interstellar medium, which include electron–positron pair production, ionization, diffusion, and Compton scattering, may influence the resulting spectra. Interestingly, a sharply broken power law has been recorded in the gamma-ray spectra of SNRs (Archambault 2017; Condon et al. 2017), AGNs (Zaborov et al. 2016), and pulsars (Ackermann 2013). However, it is difficult to determine whether they originate from GC effects or are produced by the extragalactic background light near the source (Abdalla et al. 2017). We will discuss them elsewhere.

We noticed that the above weakness can be skillfully complemented by Earth-limb gamma-ray spectra. Such method was proposed in Thompson et al. (1981), Petry (2005), and Abdol et al. (2009), and has been used to probe the dark matter (DM) signal at the GeV band. We find that the uncertainties in searching for the GC signature may be greatly reduced if the Earth-limb observation is used. Based on the above discussions, we propose that it is possible to look for the GC signature using the DARk Matter Particle Explorer (DAMPE; the DAMPE Collaboration et al. 2017) and the CALorimetric Electron Telescope (CALET; Torii et al. 2015). We will provide details in Section 4 and then give a summary at Section 5.

2. A Brief Review of Gluon Condensation

Gluons are bosons. GC has been an interesting subject for a long time. QCD analysis shows that the evolution equation of gluons becomes nonlinear due to the correlations among initial gluons at high energy. It results in a balance between gluon splitting and fusion, which is called the color glass condensate (CGC). “Condensate” here implies that the maximum occupation number of gluons is \(\sim 1/\alpha_s > 1\), although it lacks the characteristic sharp peak in momentum distribution (Jalilian-Marian et al. 1997a, 1997b; Weigert 2002).

One advance in QCD evolution equations is that the continued evolution of the CGC solution leads to a chaotic solution (Zhu et al. 2008, 2016; Zhu & Lan 2017). Most surprisingly, the dramatic chaotic oscillations produce strong shadowing and antishadowing effects; they converge gluons to a state with critical momentum \((x_c, k_c)\). According to QCD, the
number of secondary particles (which are mostly pions) at high-energy p–p(A) collisions is related to the number of gluons that participate in multiple interactions. Pions will rapidly grow when a lot of gluons enter the interaction range due to GC effects. Without concrete calculations, one can image that this will form an excess in γ-ray spectra.

Quantitative calculations of pion distributions at the p–p(A) collisions are very complicated due to nonperturbative hadronization. To simplify, we consider the secondary particles to only be pions since the multiplicities of other particles at high-energy collisions are much smaller than those of pions. Usually, these pions have a small kinetic energy (or low momentum) at the center-of-mass (C. M.) system and form the central region in the rapidity distribution. The maximum number of pions \(N_\pi\) at a given interaction energy corresponds to the case where almost all available kinetic energy of the colliding particles at the C. M. system are used to create pions. It leads to \(N_\pi \sim \sqrt{s}\). However, the data show that \(N_\pi \sim \ln s\) or \(\ln s^2\) (Anisovich et al. 1985). A possible reason is that the limited available number of gluons restricts the increase of secondaries limited available number of gluons restricts the increase of pions at the central region due to GC effects creates the maximum number \(N_\pi\) of pions. We emphasize that this assumption is a simplification rather than a necessary GC condition. In fact, we will show that while it simplifies the calculation, it does not change the GC-characteristic signature essentially. Using relativistic invariance and energy conservation, we have

\[
(2m_p^2 + 2E_{p-p(A)}m_p)^{1/2} = E_{p1}^* + E_{p2}^* + N_\pi m_\pi,
\]

where \(E_{p1}^*\) is the energy of the leading proton at the C. M. system, and \(\gamma_i\) are the corresponding Lorentz factors. Using the inelasticity \(K\) (Gaissier 1990), we set

\[
E_{p1}^* + E_{p2}^* = \left(\frac{1}{K} - 1\right)N_\pi m_\pi,
\]

and

\[
m_p\gamma_1 + m_p\gamma_2 = \left(\frac{1}{K} - 1\right)N_\pi m_\pi\gamma.
\]

One can easily get the solutions \(N_\pi(E_{p-p(A)}^\pi, E_\pi)\) for the p–p(A) collisions,

\[
\ln N_\pi = 0.5\ln E_{E_{p-p(A)}^\pi} + a, \quad \ln N_\pi = \ln E_{E_\pi} + b,
\]

where \(E_{E_{p-p(A)}^\pi} \in [E_{E_{p-p(A)}^\pi}^\max, E_{E_{p-p(A)}^\pi}^\min]\). The parameters

\[
a = 0.5\ln(2m_p) - \ln m_\pi + \ln K,
\]

and

\[
b = \ln(2m_p) - 2\ln m_\pi + \ln K.
\]

Equation (5) gives the one-to-one relation among \(N_\pi, E_{E_{p-p(A)}^\pi}\), and \(E_{E_\pi}^\GC\), which leads to a GC-characteristic spectrum.

3. The Gluon Condensation Effects in Gamma-Ray Spectra

Imagine a high-energy proton colliding with a proton or a nucleus; we have \(p + p(A) \rightarrow \pi^\pm, 0 + \) others, followed by \(\pi^0 \rightarrow 2\gamma\). The corresponding gamma flux in a general hadronic framework reads

\[
\Phi_\gamma(E_\gamma) = \Phi_0(E_\gamma)^\GC + \Phi_0(E_\gamma)\GC,
\]

where \(\Phi_0(E_\gamma)\) is the background contribution and

\[
\Phi_\gamma^\GC(E_\gamma) = C_{E_{E_{p-p(A)}^\pi}}\left(\frac{E_\gamma}{E_0}\right)^{-\beta_0} \int_{E_\gamma}^{E_\gamma^\max} \frac{dE_{E_{E_{p-p(A)}^\pi}}}{E_{E_{p-p(A)}^\pi}} \left(\frac{E_{E_{p-p(A)}^\pi}}{E_{E_{p-p(A)}^\pi}}\right)^{-\beta_0} \times \frac{ \left[ N_\pi(E_{E_{p-p(A)}^\pi}, E_\pi) \right]^{\alpha} \left(1 - \frac{1}{2}E_{E_{p-p(A)}^\pi} \right)^{\alpha} }{E_{E_{p-p(A)}^\pi}^{\alpha} \left(1 - \frac{1}{2}E_{E_{p-p(A)}^\pi} \right)^{\alpha}},
\]

where the indices \(\beta_0\) and \(\beta_p\) denote the propagating loss of gamma-rays and the acceleration mechanism of protons, respectively, and \(C_{E_{E_{p-p(A)}^\pi}}\) incorporates the kinematic factor into the flux dimension and the percentage of \(\pi^0 \rightarrow 2\gamma\). The normalized spectrum for \(\pi^0 \rightarrow 2\gamma\) is

\[
\frac{d\omega_{\pi^0\rightarrow 2\gamma}(E_\gamma, E_\pi)}{dE_\gamma} = \frac{2}{\beta_0} \ln \left[H_{\gamma; E_{E_{p-p(A)}^\pi}} \left(\frac{E_{E_{p-p(A)}^\pi}}{E_{E_{p-p(A)}^\pi}}\right)^{-\beta_0} \frac{1}{2}E_{E_{p-p(A)}^\pi} \right]
\times \frac{1}{2}E_{E_{p-p(A)}^\pi} \left(1 + \beta_2\right),
\]

where \(H(x; a, b) = 1\) if \(a \leq x \leq b\), and \(H(x; a, b) = 0\) otherwise. Inserting Equations (5) and (10) into Equation (9), we have

\[
\Phi_\gamma^\GC(E_\gamma) = C_{E_{E_{p-p(A)}^\pi}}\left(\frac{E_\gamma}{E_\gamma^\GC}\right)^{-\beta_0} \int_{E_\gamma^\GC}^{E_\gamma} \frac{dE_{E_{E_{p-p(A)}^\pi}}}{E_{E_{p-p(A)}^\pi}} \times \left(\frac{E_{E_{E_{p-p(A)}^\pi}}}{E_{E_{p-p(A)}^\pi}}\right)^{-\beta_0} \times \frac{ \left[ N_\pi(E_{E_{p-p(A)}^\pi}, E_\pi) \right]^{\alpha} \left(1 - \frac{1}{2}E_{E_{p-p(A)}^\pi} \right)^{\alpha} }{E_{E_{p-p(A)}^\pi}^{\alpha} \left(1 - \frac{1}{2}E_{E_{p-p(A)}^\pi} \right)^{\alpha}},
\]

where the lower limit of the integration takes \(E_{E_{p-p(A)}^\pi}^\GC\) (or \(E_\pi^\GC\)) if \(E_\pi \leq E_{E_{p-p(A)}^\pi}^\GC\) (or if \(E_\pi > E_{E_{p-p(A)}^\pi}^\GC\)). As a consequence,

\[
E_{E_{p-p(A)}^\pi}^\GC \Phi_\gamma^\GC(E_\gamma)
\]

\[
= \begin{cases} \frac{2C}{2\beta_0 - 1} e^{b(E_{E_{p-p(A)}^\pi}^\GC)^{3 \beta_0} - 2 b \beta_0^2} & \text{if } E_{E_{p-p(A)}^\pi}^\GC \leq E_{E_{p-p(A)}^\pi}^\GC \\ \frac{2C}{2\beta_0 - 1} e^{b(E_{E_{p-p(A)}^\pi}^\GC)^{3 \beta_0} - 2 b \beta_0^2 + 3} & \text{if } E_{E_{p-p(A)}^\pi}^\GC > E_{E_{p-p(A)}^\pi}^\GC \end{cases}
\]

It is the power law with a sharp break. The break energy \(E_{E_{p-p(A)}^\pi}^\GC\) is a direct result of the gluon distribution in...
is broken. Thus, we can introduce a simplification to the predictions of the integral in Equation (11), and it is irrelevant to the concrete form of Equation (5). The above two universal behaviors of $\Phi^{GC}$ directly arise from GC effects, and they are different from all other well-known smooth radiation spectra. We regard them to be the GC characteristics. The second power law at $E_{\gamma} > E_{\pi}^{GC}$ is a simplified result of Equations (1) and (2), where all available kinetic energies in the central region are used to create pions. We emphasize that any deformations from this power law at $E_{\gamma} > E_{\pi}^{GC}$ are allowed if our simplification is modified. Nevertheless, it does not change the above-mentioned GC characteristic. One can compare Equation (12) with the experimental data to check the validity of the simplification.

We compare the gamma-ray spectra with and without GC effects in the same hadronic framework. The second case was taken as the first evidence of a hadronic component in cosmic-ray spectra (Ackermann et al. 2013; Dermer et al. 2013). The $p-n(A)$ collisions create $\pi^0$. After a mean lifetime of $8 \times 10^{-17}$ s, $\pi^0$ decays into two gamma photons with a given energy of $m_{\pi} = 67.5$ MeV in the rest frame of the pion. This energy distribution will be substantially Doppler-shifted with respect to Earth’s rest frame due to the large kinetic energies of the $\pi^0$ mesons (Figures 2(b), (c), and (g)). In the general case, the $\pi$-spectra $N_{\pi}(E_{\pi}, \nu A)$ of $p-n(A)$ collisions in Equation (9) are complicated functions because they contain unknown hadronization dynamics in multiproduction. In the case without GC effects (Dermer et al. 2013), the authors used a two-body model at the low-energy approximation: $p + p \rightarrow \Delta, \Delta \rightarrow p + p + \pi^0$, and $\pi^0 \rightarrow 2\gamma$. The resulting $N_{\pi}$ is a smooth function of $E_{\pi}$ defined in the range $[E_{\pi}^{min}, E_{\pi}^{max}]$ (Figure 2(a)). After integrating Equation (9), one can get a smooth excess curve, which peaks at $\sim 1$ GeV in the $E_{\gamma}^{max} \Phi - E_{\gamma}$ plot (see Figure 2(c)). Note that the factor $E_{\gamma}^{-\beta_{\gamma}}$ is ignored in this example. The results are demonstrated for the W44 and IC 443 gamma-ray spectra (Ackermann et al. 2013).

We now consider the GC effects (Figures 2(d)–(h)). A main difference is that $N_{\pi}$ takes the form of Equation (5), which is defined in the range $E_{\pi} \in [E_{\pi}^{GC}, E_{\pi}^{max}]$. The conditions $E_{\gamma} < E_{\pi}^{GC}$ and $E_{\pi} > E_{\pi}^{GC}$ divide the integral into two parts.

Figure 2. Schematic diagrams for $\gamma$-ray spectra in the hadronic model. (a)–(c) without GC effects; (d)–(h) with GC effects.

Thus, the power law is broken at $E_{\pi}^{GC}$ (see dashed lines (or solid lines)) in Figure 2(h) if without (or with) the corrections of $E_{\pi}^{-\beta_{\gamma}}$ and $E_{p}^{-\beta_{\gamma}}$.

Equation (12) is the solution of the analytic form of GC-characteristic spectra rather than a numerical simulation. Their parameters have a definite physical meaning. Therefore, a deviation from model Equations (1) and (2) may break the line at $E_{\gamma} > E_{\gamma}^{GC}$ in the log–log representation. The pure power law at $E_{\gamma} < E_{\gamma}^{GC}$ in Equation (12) is irrelevant to Equation (5), unless the power-law form $E_{\gamma}^{-\beta_{\gamma}}$ is broken. Thus, we can modify our assumption in Equation (5) according to the derivations of the predicted broken power law, Equation (12).

4. The Earth-limb Photon Spectra at the GeV–TeV Band

An observation of the Earth-limb gamma-ray spectrum is shown in Figure 3. Cosmic rays (mainly protons) entering the atmosphere produce a lot of secondary particles including photons due to $p$–air collisions. A considerable amount of these $\gamma$-rays spread toward the dense atmosphere and form high-energy showers, which may mix with the $\gamma$-rays originating from the $p$–air interactions. However, part of the oblique-incidence photons propagate toward the thin atmosphere, and we can ignore the contributions of the air shower. These $\gamma$-ray spectra depend on the $p$–air cross section and the spectrum of the incident protons. One can measure this so-called Earth-limb $\gamma$-ray spectrum by changing the orbit and direction of the detector.

In contrast to the GDE, the contribution from the inverse Compton scattering of cosmic-ray electrons to the Earth-limb emission is negligible, because the atmosphere lacks dense soft photons and strong electron flux. It avoids the debate between leptonic and hadronic models. The spectrum of incident protons near the atmosphere is well known, and the spectrum index is $\beta_{p} \approx 2.75$, while the target nuclei (mainly nitrogen and oxygen) and their abundances are completely fixed. Besides, the observation at the top of the atmosphere may reduce the influence of the electromagnetic shower.

In order to illustrate the GC spectra in the $p$–N(O) collisions, we need to know the value of $E_{\pi}^{GC}$, which is target-dependent. Because the nonlinear term of the QCD evolution equation should be rescaled by $A^{1/3}$, $E_{\pi}^{GC}$ decreases

Figure 3. Schematic of the Earth-limb gamma-ray production by cosmic rays from Earth’s atmosphere (reproduced from https://fermi-hero.readthedocs.io/en/latest/_images/earth_limb_gammams.png).
The GC signature in the Earth-limb gamma-ray spectrum, which is not scaled. $\beta_2 = 0$ and $\beta_3 = 2.75$. The resulting spectrum presents a GC-characteristic sharp peak. The dotted line is the background $\sim E^{-2.75}$.

Figure 4. The GC signature in the Earth-limb gamma-ray spectra, which is not scaled. $\beta_3 = 0$ and $\beta_2 = 2.75$. The resulting spectrum presents a GC-characteristic sharp peak. The dotted line is the background $\sim E^{-2.75}$.

The cross section $\sigma_{p-p}$ was estimated using the distribution of the shower maximum slant depth $X_{\text{max}}$ where the interaction length and consequently $\sigma_{p-p}$ are related to the exponential tail of the $X_{\text{max}}$ distribution (and its exponential tail) in the cascade model. The result from the Telescope Array does not show a big increment effect in $\sigma_{p-p}$ until $\sqrt{\beta} = 95$ TeV (Hanlon & Abbasi 2017). However, the cascade method has a fundamental limitation. Several important parameters are uncertain (Gaisser 1990). Besides, the GC effects may disappear quickly at the beginning of collisions due to the energy loss of the leading proton. Therefore, we do not regard the Telescope Array data as a constraint on the value of $E_{\gamma}^{GC}$ in this work.

The bright gamma-ray emission from Earth’s limb was observed by the SAS-2 (Thompson et al. 1981), EGRET (Petry 2005), and Fermi-LAT (Ackermann et al. 2014) instruments. Gamma-ray energy spectra from Earth’s limb follow a power law $\sim E_{\gamma}^{-2.75}$, and their measurements reach $E_{\gamma} \sim 400$ GeV (Ackermann et al. 2014). If this law is valid at even higher energies, one can estimate that the $\gamma$-ray flux will be reduced by an order of three at $E_{\gamma} = 4$ TeV (or by an order of four at $E_{\gamma} = 10$ TeV). On the other hand, we have estimated that the inelastic cross section of $p-p$ collision increases by an order of four due to GC effects (Zhu & Lan 2017). Therefore, observing the GC signature in the Earth-limb $\gamma$-energy spectrum is possible. We noticed that DAMPE and CALET have higher resolution and adjustable observation methods. The energy range for DAMPE is 5 GeV to $\sim 10$ TeV, which is similar to that of CALET. They are suitable for probing the GC signature in the Earth-limb gamma-ray spectrum. Figure 4 gives a schematic diagram for the contributions of the GC effects to $\Phi_{\gamma}^{GC}(E_{\gamma})$, where the resulting curve is not scaled. A sharp peak originating from the GC effects in the Earth-limb $\gamma$-ray energy spectrum is different from all other smooth excesses, and we can easily recognize it.

The gamma-ray signal of dark matter (DM) has aroused great interest. If DM annihilates to gamma-rays directly, one can get a gamma-ray line signature. While DM produces leptons and quarks, the gamma-ray spectrum as a final product presents an “excess” or a smoothly broken power law. These two forms are obviously different from the GC effects, which shows a sharply broken power law. Besides, it is impossible that DM generates a new Earth-limb gamma-ray signal through DM annihilation in the atmosphere, since the cross section and the DM density in the atmosphere region are all very small, and the corresponding gamma-ray flux is negligible. Therefore, we can distinguish the GC signature from DM signals in Earth-limb gamma-ray spectra.

5. Summary

A research of QCD evolution dynamics shows that the gluons in protons may converge to a state with a critical momentum at a high-energy range. GC effects should produce a lot of extra secondary pions at the central region of the rapidity distributions. Without concrete calculations, one can imagine that it will induce a gamma-ray excess if the interaction energy of the $p-p(A)$ collisions is larger than a critical scale. A quantitative analysis presents the GC-characteristic gamma-ray spectrum, which is a sharply broken power law. We suggest observing Earth-limb gamma-ray spectra at the GeV–TeV band using the DAMPE and CALET installations in orbit to probe the GC signature.

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