Possible Evidence for the Gluon Condensation Effect in Cosmic Positron and Gamma-Ray Spectra

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Abstract

The gluon condensation (GC) effect in cosmic proton–proton collisions at high energy is used to explain an excess in the positron spectrum observed by the Alpha Magnetic Spectrometer. We find that this excess may originate from the GC effect in Tycho’s supernova remnant.

Unified Astronomy Thesaurus concepts: Gamma-ray astronomy (628); High energy astrophysics (739); Galactic cosmic rays (567)

1. Introduction

Precise measurement of the positron flux in cosmic rays (CRs) with the Alpha Magnetic Spectrometer (AMS) on the International Space Station exhibits a complex energy dependence (Aguilar et al. 2019). The results show that a significant excess is added on a diffuse background around 300–400 GeV of the positron energy. The new extra source is predominantly suggested as dark matter annihilation or other astrophysical sources. The resulting key point is: where is this local source? We cannot “see” dark matter. We also cannot track the positrons because of their complex trajectories in interstellar space. While if we know this extra source radiates a characteristic gamma-ray spectrum, which is closely related to excess positrons, then we can find the extra source. The gluon condensation (GC) mechanism provides this possibility.

Gluons inside protons dominate proton collisions at high energy and their distributions obey the evolution equations based on quantum chromodynamics (QCD). QCD analysis shows that the evolution equations will become nonlinear due to the initial gluon correlations at high energy and these will result in a chaotic solution beginning at a threshold energy (Zhu et al. 2008, 2016). Most surprisingly, dramatic chaotic oscillations produce strong shadowing and antishadowing effects, which converge gluons to a state at a critical momentum (Zhu & Lan 2017). This is the GC effect in protons. GC should induce significant effects in proton collision processes, provided the collision energy is higher than the GC threshold $E_{GC}^{\text{pp}}$. The GC model was used to explain the excess in cosmic gamma-ray and electron–positron fluxes (Feng et al. 2018; Zhu et al. 2018).

In this work we present new evidence that shows that the positron excess observed by the AMS originates from the GC effect in Tycho’s supernova remnant (SNR). Our idea is straightforward. High-energy gamma-ray and electron–positron fluxes in CRs may originate from leptonic processes (bremstrahlung, inverse Compton scattering, and electromagnetic acceleration); they are also products of hadronic processes, where $p + p \rightarrow \pi^0 \rightarrow 2\gamma$, and through a strong electromagnetic field inside the source: $\gamma \rightarrow e^+ + e^-$. We take a hadronic framework but add the GC effect in this work. When a large number of gluons condense in a critical momentum space, this must inevitably increase the number of secondary particles ($\pi, \gamma, e^+$ and $e^-$) at the corresponding energy threshold, and break the power law. In particular, the positron excess is always accompanied by a special broken gamma-ray spectrum since considerable parts of these two fluxes (see Equations (2.10) and (2.13)) are interrelated. This implies that the gamma-ray spectrum corresponding to the excess positron flux has a characteristic shape. Thus, we can judge which source produces the AMS positron excess using a directly observable gamma-ray spectrum.

We give the relevant formulas of the GC model for the explanation of gamma-ray and positron flux in Section 2. A detailed description can be found in Feng et al. (2018) and Zhu et al. (2018). In Section 3 we analyze Tycho’s gamma-ray spectrum and compare it with the AMS positron flux. We find that their consistency with theoretical predictions reaches $\chi^2/\text{dof} = 0.54$ and 0.45, respectively. This result strongly suggests that the positron excess observed by the AMS mainly originates from the nearby Tycho’s SNR. Discussions and a summary are given in Section 4.

2. The GC Model

High-energy gamma-ray and electron–positron fluxes in CRs may originate from the following processes: $p + p \rightarrow \pi^0 \rightarrow 2\gamma$ and $\gamma \rightarrow e^+ + e^-$. The number of secondary pions in proton–proton collision is determined by the gluon distribution inside the protons (Field & Feynman 1977). Usually these pions have a small kinetic energy (or low momentum) in the center-of-mass (C.M.) system and form the central region in the rapidity distribution. Gluons in protons may condense at a critical momentum $(x_c, k_c)$. One can image that this GC effect should appear in CR spectra. A large number of gluons in the central region due to GC effects creates the maximum number $N_c$ of pions, which take up all the available kinetic energy, where we neglect other secondary particles. Using general relativistic invariance and energy conservation, we have

\begin{equation}
(2m_\gamma^2 + 2E_{p-p}m_p)^{1/2} = E_{p1}^* + E_{p2}^* + N_c m_\pi, \tag{2.1}
\end{equation}

\begin{equation}
E_{p-p} + m_p = m_{p1}\gamma_1 + m_{p2}\gamma_2 + N_c m_\pi \gamma, \tag{2.2}
\end{equation}

where $E_{p_i}^*$ is the energy of the leading proton in the C.M. system, and $\gamma_i$ are the corresponding Lorentz factors. Using the
where the GC effect enters \( \Phi_{\gamma}^{GC}(E_{\gamma}) \) via Equation (2.5). The spectral indices \( \beta_{p} \) and \( \beta_{\gamma} \) denote the propagating loss of gamma-rays and protons, respectively; \( C_{e} \) incorporates the kinematic factor with the flux dimension and the percentage of \( \pi^{0} \to 2\gamma \). The normalized spectrum for \( \pi^{0} \to 2\gamma \) is

\[
\frac{d\omega_{\pi^{0}\to\gamma\gamma}(E_{\gamma}, E_{\pi})}{dE_{\gamma}} = \frac{2}{\beta_{p}E_{\pi}} H \left[ E_{\gamma}, \frac{1}{2}E_{\pi}(1 - \beta_{p}), \frac{1}{2}E_{\pi}(1 + \beta_{p}) \right],
\]

where \( H(x; \alpha, \beta) = 1 \) if \( \alpha \leq x \leq \beta \), and \( H(x; \alpha, \beta) = 0 \) otherwise; \( \beta_{\pi} \sim 1 \). Inserting Equations (2.5)–(2.7) and (2.9) into Equation (2.8), we have

\[
\Phi_{\gamma}^{GC}(E_{\gamma}) = C_{e} \left( \frac{E_{\gamma}}{E_{\pi}^{GC}} \right)^{-\beta_{p}} \int_{E_{\gamma}^{GC} \text{ or } E_{\gamma}}^{\infty} dE_{\pi} \left( \frac{E_{\pi}-E_{\gamma}}{E_{\pi}^{GC}} \right)^{-\beta_{\pi}}
\times N_{\pi}(E_{\pi}, E_{\gamma}) \frac{2}{\beta_{\pi}E_{\pi}},
\]

where the lower limit of the integration takes \( E_{\pi}^{GC} \) (or \( E_{\gamma} \)) if \( E_{\gamma} \leq E_{\pi}^{GC} \) (or if \( E_{\gamma} > E_{\pi}^{GC} \)). In consequence,

\[
E_{\gamma}^{2} \Phi_{\gamma}^{GC}(E_{\gamma}) = \begin{cases} \frac{2e^{b}C_{e}^{2}}{2\beta_{p}-1}(E_{\pi}^{GC})^{3} \left( \frac{E_{\gamma}}{E_{\pi}^{GC}} \right)^{-\beta_{\gamma}+2} & \text{if } E_{\gamma} \leq E_{\pi}^{GC} \\ \frac{2e^{b}C_{e}^{2}}{2\beta_{p}-1}(E_{\pi}^{GC})^{3} \left( \frac{E_{\gamma}}{E_{\pi}^{GC}} \right)^{-\beta_{\gamma}-2\beta_{p}+3} & \text{if } E_{\gamma} > E_{\pi}^{GC}. \end{cases}
\]

Interestingly, this solution shows a typical broken power law.

We add the contributions of \( \gamma \to e^{+} + e^{-} \) to Equation (2.8) and get the following positron spectrum:

\[
\Phi_{e^{\pm}}^{GC}(E_{e^{\pm}}) = \Phi_{e^{\pm}}^{0}(E_{e^{\pm}}) + \Phi_{e^{\pm}}^{GC}(E_{e^{\pm}}),
\]

where \( \Phi_{e^{\pm}}^{0} \) is the background flux of positrons, and

\[
\Phi_{e^{\pm}}^{GC}(E_{e^{\pm}}) = C_{e} \left( \frac{E_{e^{\pm}}}{E_{\pi}^{GC}} \right)^{-\beta_{\gamma}} \int_{E_{\gamma}}^{E_{e^{\pm}} \text{ or } E_{\gamma}} E_{\gamma} \frac{2e^{b}C_{e}^{2}}{2\beta_{p}-1}(E_{\pi}^{GC})^{3} \left( \frac{E_{e^{\pm}}}{E_{\pi}^{GC}} \right)^{-\beta_{\gamma}+2} N_{\pi}(E_{\pi}, E_{\gamma}) \frac{2}{\beta_{\pi}E_{\pi}} dE_{\gamma}
\times \int_{E_{\gamma}}^{E_{e^{\pm}} \text{ or } E_{\gamma}} N_{\pi}(E_{\pi}, E_{\gamma}) \frac{2}{\beta_{\pi}E_{\pi}} dE_{\gamma}
\times \int_{E_{\gamma}}^{E_{e^{\pm}} \text{ or } E_{\gamma}} \frac{2e^{b}C_{e}^{2}}{2\beta_{p}-1}(E_{\pi}^{GC})^{3} \left( \frac{E_{e^{\pm}}}{E_{\pi}^{GC}} \right)^{-\beta_{\gamma}-2\beta_{p}+3} N_{\pi}(E_{\pi}, E_{\gamma}) \frac{2}{\beta_{\pi}E_{\pi}} dE_{\gamma}
\]

\[
\times \left( \frac{2e^{b}C_{e}^{2}}{2\beta_{p}-1}(E_{\pi}^{GC})^{3} \left( \frac{E_{e^{\pm}}}{E_{\pi}^{GC}} \right)^{-\beta_{\gamma}-2\beta_{p}+3} N_{\pi}(E_{\pi}, E_{\gamma}) \frac{2}{\beta_{\pi}E_{\pi}} dE_{\gamma} \right)
\]

\[
\times \left( \frac{2e^{b}C_{e}^{2}}{2\beta_{p}-1}(E_{\pi}^{GC})^{3} \left( \frac{E_{e^{\pm}}}{E_{\pi}^{GC}} \right)^{-\beta_{\gamma}-2\beta_{p}+3} N_{\pi}(E_{\pi}, E_{\gamma}) \frac{2}{\beta_{\pi}E_{\pi}} dE_{\gamma} \right)
\]

\[
\times \left( \frac{2e^{b}C_{e}^{2}}{2\beta_{p}-1}(E_{\pi}^{GC})^{3} \left( \frac{E_{e^{\pm}}}{E_{\pi}^{GC}} \right)^{-\beta_{\gamma}-2\beta_{p}+3} N_{\pi}(E_{\pi}, E_{\gamma}) \frac{2}{\beta_{\pi}E_{\pi}} dE_{\gamma} \right)
\]

\[
\times \left( \frac{2e^{b}C_{e}^{2}}{2\beta_{p}-1}(E_{\pi}^{GC})^{3} \left( \frac{E_{e^{\pm}}}{E_{\pi}^{GC}} \right)^{-\beta_{\gamma}-2\beta_{p}+3} N_{\pi}(E_{\pi}, E_{\gamma}) \frac{2}{\beta_{\pi}E_{\pi}} dE_{\gamma} \right)
\]

\[
\times \left( \frac{2e^{b}C_{e}^{2}}{2\beta_{p}-1}(E_{\pi}^{GC})^{3} \left( \frac{E_{e^{\pm}}}{E_{\pi}^{GC}} \right)^{-\beta_{\gamma}-2\beta_{p}+3} N_{\pi}(E_{\pi}, E_{\gamma}) \frac{2}{\beta_{\pi}E_{\pi}} dE_{\gamma} \right)
\]

\[
\times \left( \frac{2e^{b}C_{e}^{2}}{2\beta_{p}-1}(E_{\pi}^{GC})^{3} \left( \frac{E_{e^{\pm}}}{E_{\pi}^{GC}} \right)^{-\beta_{\gamma}-2\beta_{p}+3} N_{\pi}(E_{\pi}, E_{\gamma}) \frac{2}{\beta_{\pi}E_{\pi}} dE_{\gamma} \right)
\]

\[
\times \left( \frac{2e^{b}C_{e}^{2}}{2\beta_{p}-1}(E_{\pi}^{GC})^{3} \left( \frac{E_{e^{\pm}}}{E_{\pi}^{GC}} \right)^{-\beta_{\gamma}-2\beta_{p}+3} N_{\pi}(E_{\pi}, E_{\gamma}) \frac{2}{\beta_{\pi}E_{\pi}} dE_{\gamma} \right)
\]

\[
\times \left( \frac{2e^{b}C_{e}^{2}}{2\beta_{p}-1}(E_{\pi}^{GC})^{3} \left( \frac{E_{e^{\pm}}}{E_{\pi}^{GC}} \right)^{-\beta_{\gamma}-2\beta_{p}+3} N_{\pi}(E_{\pi}, E_{\gamma}) \frac{2}{\beta_{\pi}E_{\pi}} dE_{\gamma} \right)
\]

\[
\times \left( \frac{2e^{b}C_{e}^{2}}{2\beta_{p}-1}(E_{\pi}^{GC})^{3} \left( \frac{E_{e^{\pm}}}{E_{\pi}^{GC}} \right)^{-\beta_{\gamma}-2\beta_{p}+3} N_{\pi}(E_{\pi}, E_{\gamma}) \frac{2}{\beta_{\pi}E_{\pi}} dE_{\gamma} \right)
\]

Note that after taking the average over all possible directions, the energy of pair creation is uniformly distributed from zero to a maximum value, i.e.,

\[
\frac{d\omega_{\gamma\rightarrow e^{\pm}e^{\pm}}(E_{\gamma}, E_{e^{\pm}})}{dE_{e^{\pm}}} = \frac{1}{E_{\gamma}}.
\]

Equation (2.13) shows an excess near \( E_{\pi}^{GC} \) in the positron spectrum.

3. Evidence for the GC Source

Measurements of CR positron flux by the AMS (Aguilar et al. 2019) show a significant excess peaking at \( \sim 300 \text{ GeV} \) (or \( \sim 400 \text{ GeV} \) if subtracting the contribution of the diffuse background). We attempt to understand this using the GC model.

According to the GC model, Equations (2.11) and (2.13), if the excess of the positron spectrum at 400 GeV arises due to the GC effect, we predict: (i) one can observe gamma-ray emission originating from the same GC source in a galaxy,
which has a characteristic spectrum with a broken power law on both sides of $E_e \approx 400$ GeV; (ii) the spectral indexes $\beta_p$ and $\beta_e$ of this gamma-ray spectrum are same as that of the positron spectrum; (iii) the value of $\gamma_p$ for this GC source is larger than that of other similar gamma-ray sources since it is closest to the Earth; (iv) this GC source has a relatively large value of $\beta_e$ since it implies a strong $\gamma \rightarrow e^+ + e^-$ conversion mechanism.

Interestingly, SNR G120.1+1.4 is one such possible GC source. Historically it was observed by Tycho in 1572 and hereafter it is referred to as Tycho. An updated gamma-ray spectrum of Tycho’s SNR by VERITAS and Fermi-LAT shows a clear broken power law. Although some other models may fit the updated gamma-ray spectra after adjusting their parameters (Archambault et al. 2017; Bykov et al. 2018; Cristofari et al. 2018), in a new approach, we use the GC effect (Equation (2.11)) to fit Tycho’s spectrum. Figure 1 gives our fitted gamma-ray spectrum and the comparison with the Tycho’s spectrum, where the GC threshold $E_{\gamma,GC} = 400$ GeV, $\beta_p^{Tycho} = 0.89$, $\beta_e^{Tycho} = 2.14$, and $C_p^{Tycho} = 6 \times 10^{-10}$ GeV m$^{-2}$ s$^{-1}$ are fixed using VERITAS and Fermi-LAT data. We get a reasonable fitting quality criterion:

$$\chi^2/dof = \sum_i \frac{(\Phi_i^{pre} - \Phi_i^{obs})^2}{\sigma_{\gamma,i}^2 + \sigma_{\delta,i}^2} \frac{1}{dof} = \frac{3.24}{6} = 0.54.$$  

(3.1)

The point at the high-energy end of the VERITAS data is the most discrepant point relative to the fit. We notice that the GC threshold is nuclear mass $A$-dependent (see the next section). A rough estimation shows that the GC effect in $p-p$ collisions may contribute an excess to the gamma-ray and electron-positron spectra above 20 TeV (Zhu et al. 2018). We await more sensitive future measurements.

Now we assume that the excess of the positron spectrum recorded by the AMS arises from Tycho’s SNR. One can write the total positron flux, which is the sum of the source term Equation (2.13) and a diffuse background term

\begin{equation}
\Phi^0_{e^+}(E) = C_d \frac{E^2}{E_0^2} \left( \frac{\hat{E}}{E_0} \right)^{\gamma},
\end{equation}

(Aguilar et al. 2013):

where $\hat{E} = E + E_0$. We substitute the fixed parameters $E_{\gamma,GC} = 400$ GeV, $\beta_p^{GC} = 0.89$ and $\beta_e^{GC} = 2.14$ into Equation (2.13) and adjust $\beta_p^{\gamma}$, $C_p^{\gamma}$ and the remaining parameters in Equation (3.2). Note that $\beta_p^{\gamma} = \beta_p^{Tycho}$ and $\beta_e^{\gamma} = \beta_e^{Tycho}$ are fixed. The result is presented in Figure 2. The fitting $\chi^2/dof = 19.65/44 = 0.45$.

4. Discussions and Summary

The conclusions of this work are based on Equations (2.1) and (2.2) under the GC condition. This is a plausible but unproven assumption. The data from a range of SNRs including Tycho’s can be approximately described by several models, including leptonic and hadronic components without the GC effect. However, the GC effect in the hadronic framework can connect two kinds of astrophysical observations perfectly, namely the positron excess in the AMS and the broken power law for Tycho’s gamma-ray spectrum. This feature is what we wish to emphasize.

To illustrate the sensitivity of the fitting quality to the selection of the parameters, we present the contributions of the GC source to the positron and gamma-ray fluxes with different values of $\beta_p$ in Figures 3 and 4, respectively. The sensitivity of the results to the parameter selection shows that our $\chi^2/dof \simeq 0.5$ is not an accidental coincidence. It appears that the high-energy data points of AMS do not place significant constraints on the value of $\beta_p$; rather it is the low-energy Fermi-LAT points that constrain $\beta_p$. However, considering the correlation between the low-energy and high-energy points, the constraint in Figures 3 and 4 is on the parameter $\beta_p$ is strict.
The results in Section 3 are consistent with our predictions: (i) $E_{\gamma}^{GC} = 400$ GeV; (ii) $\beta_{\gamma}^{Tycho} = \beta_{\gamma}^{p}$ and $\beta_{\gamma}^{Tycho} = \beta_{\gamma}^{p}$.

Finally, we should explain why no GC signals are observed at the Large Hadron Collider (LHC). The GC threshold $E_{\gamma}^{GC}$ is target $A$-dependent, since the nonlinear term of the QCD evolution equation should be re-scaled by $A^{1/3}$ and $E_{\gamma}^{GC}$ decreases with increasing $A$ (Zhu & Lan 2017). However, $A$-dependence of $E_{\gamma}^{GC}$ is a complicated problem, related to the distribution and structure of the GC source. We have no available input distributions of the nonlinear QCD evolution to precisely predict the GC threshold. According to a rough estimation in Zhu & Lan (2017), we have $E_{\gamma}^{GC} > E_{\gamma}^{GC} > E_{\gamma}^{GC}$. Using Equations (2.1)–(2.7), the center-of-mass energy corresponding to $E_{\gamma}^{GC} = 400$ GeV is

$$\sqrt{S_{A-A}^{GC}} = \sqrt{2m_{p}E_{\gamma}^{GC}} = \sqrt{2m_{p}e^{b-a}E_{\gamma}^{GC}} = 5.5 \text{ TeV.} \quad (4.1)$$

The ALICE and ATLAS collaborations at the LHC have measured Pb–Pb (and p–Pb) collisions up to $\sqrt{S_{A-A}} = 5.02$ TeV (and $\sqrt{S_{Pb-Pb}} = 8.16$ TeV) (Rode 2019; Aad et al. 2019). We consider that $\sqrt{S_{A-A}^{GC}} > 5$ TeV and $\sqrt{S_{Pb-Pb}^{GC}} > 8$ TeV; this implies that the GC effect is entering (or will enter) measurable energy range.

In summary, QCD research predicts that gluons in protons may condense at a critical momentum in high-energy proton–proton collisions. We use the GC model to explain two seemingly completely different events in CR spectra: an excess in positron flux and the broken power law in the gamma-ray spectrum of Tycho. We consider that the excess in the CR positron spectrum observed by the AMS originates mainly from the GC effect in Tycho’s SNR.

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