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COMPTONIZATION OF COSMIC MICROWAVE BACKGROUND BY COLD ULTRARELATIVISTIC ELECTRON-POSITRON PULSAR WIND AND ORIGIN OF ∼130 GeV LINES

Previously, an astrophysical explanation of the narrow gamma-ray line-like feature(s) at ∼100 GeV from the Galactic Center region observed by Fermi/LAT [2] was proposed in [1]. The model of [1] is based on the inverse Compton scattering of external ultraviolet/X-ray radiation by a cold ultrarelativistic e^+-e^- pulsar wind. We will show that the extra broad ∼30 MeV component should arise from the Comptonization of cosmic microwave background radiation. We estimate the main parameters of this component and show that it can be detectable with MeV telescopes such as CGRO/COMPTEL. The location of the CGRO/COMPTEL unidentified source GRO J1823-12 close to the excess of the 105–120-GeV emission (Region 1 of [2]) can be interpreted as an argument in favor of the astrophysical model of the narrow feature(s) at ∼100 GeV.

Keywords: gamma-ray line, Galactic Center, pulsar wind, inverse Compton effect, cosmic microwave background radiation.

1. Introduction

Previous claims about the presence of narrow line-like γ-ray feature(s) around 100–130 GeV observed by a Large Area Telescope (LAT) on the Fermi gamma-ray observatory near the Galactic Center have been received a lot of attention. Proposed interpretations include dark matter annihilation [5–9], dark matter decay [9–11], systematic effects [2–4] and an astrophysical mechanism – comptonization (in the deep Klein–Nishina regime) of a cold ultrarelativistic e^+-e^- pulsar wind by the external UV/X-ray emission [1].

In this paper, we discuss the astrophysical mechanism proposed by [1] in more details. We will show that, in addition to ∼100 GeV line emission, a broad γ-ray component should be produced due to the comptonization of the cosmic microwave background (CMB) radiation. For ∼100 GeV astrophysical lines, the typical energy of this component should be several tens of MeV. The further detection of unidentified MeV sources with positions coinciding with the GeV line excesses (such as GRO J1823-12 [12] located very close to the 105–120 GeV excess (Region 1 of [2])) will argue in favor of the astrophysical origin of GeV lines.

2. Model Description

The model of [1] is based on the inverse Compton scattering of energetic (UV and X-ray) photons by a cold ultrarelativistic e^+-e^- pulsar wind accelerated in a vicinity of the pulsar magnetosphere (see, e.g., [13] for details). In this case, the scattering occurs in the deep Klein–Nishina regime, where the typical energy of a scattered photon is close to that of the initial electron. If the conversion efficiency is large enough, the mechanism of [1] can produce narrow ∼100 GeV lines with flux $F_{\rm line} \sim 10^{-10}$ erg cm^{-2} s^{-1} consistent with

Fermi/LAT observations. Given the distance to the Galactic center ~ 8 kpc [14], such flux corresponds to a luminosity of $\sim 10^{36}$ erg/s.

In this paper, we assume the validity of the model proposed in [1]. In this case, one should also detect a softer continuum component due to the Compton scattering of CMB radiation on the e^+-e^- wind. In the Thomson regime, the average energy of scattered CMB photons is [1] [15]

$$\langle\epsilon_1\rangle = \frac{4}{3}\gamma^2\langle\epsilon_{\text{CMB}}\rangle \approx 34\left(\frac{\gamma}{2\times10^5}\right)^2 \text{ MeV}, \tag{1}$$

where $\gamma \sim 2\times10^5$ is the Lorentz factor of the cold electron-positron wind (able to produce $\sim$100 GeV photon line [1]), $\langle\epsilon_{\text{CMB}}\rangle \approx 2.7\ T_{\text{CMB}} = 6.3\times10^{-4}$ eV is the average energy of CMB photons. The total flux of this softer component equals

$$F_{\text{soft}} = F_{\text{line}} \times \frac{(dE/dt)_{\text{T}}}{(dE/dt)_{\text{dKN}}}, \tag{2}$$

where $(dE/dt)_{\text{T}}$ and $(dE/dt)_{\text{dKN}}$ are the average energy loss rates of a single e^- or e^+ in the Thomson and deep Klein–Nishina regimes, respectively. To calculate $(dE/dt)_{\text{T}}$ and $(dE/dt)_{\text{dKN}}$, we use expressions (2.18) and (2.57) from [15]:

$$(dE/dt)_{\text{T}} = -\frac{4}{3}\sigma_{\text{T}}c\gamma^2\mathcal{E}_{\text{CMB}}, \tag{3}$$

$$(dE/dt)_{\text{dKN}} = -\frac{3}{8}\sigma_{\text{T}}m_e^2c^5\times$$
$$\times\int\frac{n_{\text{ext}}(\epsilon)d\epsilon}{\epsilon}\left[\ln\left(\frac{4\epsilon\gamma}{m_ec^2}\right)-\frac{11}{6}\right]. \tag{4}$$

Here, σ_{T} is the Thomson cross-section, $\mathcal{E}_{\text{CMB}} \approx 0.26$ eV/cm^3 is the CMB energy density, $n_{\text{ext}}(\epsilon)$ is the density distribution of external radiation leading to the production of $\sim$100 GeV lines.

According to [1], to explain the smallness of the measured width of $\sim$100 GeV lines, the energy of external photons should be high enough,

$$\epsilon \gtrsim \epsilon_{\text{min}} = 20\left(\frac{\gamma}{2\times10^5}\right)^{-1} \text{ eV}, \tag{5}$$

to ensure that the corresponding Compton scattering occurs in the deep Klein–Nishina regime. In [1], two possible origins of the external emission with such an energy were proposed:

- thermal emission from the surface of the neutron star;
- thermal emission from the hot companion star (in the case of binary pulsar).

In both cases, the density distribution of external radiation can be approximated with that of rescaled blackbody radiation:

$$n_{\text{ext}}(\epsilon) = \frac{15\mathcal{E}_{\text{ext}}}{\pi^4T_{\text{ext}}^4}\frac{\epsilon^2}{\exp(\epsilon/T_{\text{ext}})-1}, \tag{6}$$

where $\mathcal{E}_{\text{ext}}$ and T_{ext} are the total energy density and the temperature of the external radiation. Substituting (6) into (4), we obtain, in accordance with expression (2.59) of [15],

$$(dE/dt)_{\text{dKN}} = -\frac{15}{16\pi^2}\sigma_{\text{T}}c\gamma^2\mathcal{E}_{\text{ext}}\mathcal{F}\left(\frac{\gamma T_{\text{ext}}}{m_ec^2}\right), \tag{7}$$

where

$$\mathcal{F}(x) = \frac{1}{x^2}\left[\ln(4x)-\frac{5}{6}-C_E-C_l\right],\ x \gg 1,$$

$C_E \approx 0.5772$ is Euler's constant,

$$C_l = \frac{6}{\pi^2}\sum_{k=2}^{\infty}\frac{\ln k}{k^2} \approx 0.5700.$$

Substituting (3) and (7) to (2), we obtain

$$F_{\text{soft}} = F_{\text{line}}\times\frac{64\pi^2}{45}\frac{\mathcal{E}_{\text{CMB}}}{\mathcal{E}_{\text{ext}}\mathcal{F}\left(\frac{\gamma T_{\text{ext}}}{m_ec^2}\right)}. \tag{8}$$

The ranges for the function $\mathcal{F}$ can be obtained from numerical estimates of T_{ext}. For neutron stars, $T_{\text{ext}} \lesssim 1$ keV (see, e.g., [16]), so $\mathcal{F} \gtrsim 4\times10^{-5}$. On the other hand, for small T_{ext}, the function $\mathcal{F}$ has a maximum, $\mathcal{F} \lesssim 0.0560$. For these values of $\mathcal{F}$, we obtain the following relation between $\mathcal{E}_{\text{ext}}$, F_{soft}, and F_{line}:

$$65 \text{ eV/cm}^3 \lesssim \mathcal{E}_{\text{ext}}\frac{F_{\text{soft}}}{F_{\text{line}}} \lesssim 9\times10^4 \text{ eV/cm}^3. \tag{9}$$

To calculate F_{soft}, we use the CGRO/COMPTEL observations of GeV line sources in a MeV band. Interestingly, one of the detected CGRO/COMPTEL sources, GRO J1823-12 [12] (see also 3EG J1823-1314 [17]) is located very close to Reg. 1 of [2], where the $\sim$4.7σ excess at 105-120 GeV has been found [2]. The flux from GRO J1823-12 in the 10–30 MeV band

[1] Throughout this paper, we use notations from [15].

is $(1.0 \pm 0.2) \times 10^{-5}$ photon cm^{-2} s^{-1} [12], the corresponding flux from 3EG J1823-1314 is $(2.7 \pm 0.5) \times$ $\times\, 10^{-5}$ photon cm^{-2} s^{-1} [17], which gives us the estimate for $F_{\rm soft}$ detectable with CGRO/COMPTEL near the Galactic Center region

$$F_{\rm soft} \simeq \left(10^{-10}\text{–}10^{-9}\right)\ \text{erg cm}^{-2}\ \text{s}^{-1}.$$

To detect the softer component from $\sim$100 GeV line emitter candidates (with $F_{\rm line} \sim 10^{-10}$ erg cm^{-2} s^{-1}) with CGRO/COMPTEL, the value of $\mathcal{E}_{\rm ext}$ should be in the range

$$10\ \text{eV/cm}^3 \lesssim \mathcal{E}_{\rm ext} \lesssim 10^5\ \text{eV/cm}^3. \qquad (10)$$

These values of $\mathcal{E}_{\rm ext}$ are expected for the Galactic Ridge region [18, 19].

3. Conclusions

We showed that the astrophysical mechanism of $\sim$100 GeV line production proposed in [1] leads to the presence of the additional softer broadened component originated from the inverse Compton scattering of CMB radiation by the cold ultrarelativistic electron-positron wind. The typical energy of the softer component should be around 30 MeV and can thus be detected by MeV telescopes such as CGRO/COMPTEL.

The further identification of this component with instruments operating in the MeV band may lead to the confirmation of the astrophysical origin of the $\sim$100 GeV line(s).

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1. F. Aharonian, D. Khangulyan, and D. Malyshev, Astron. Astrophys. **547**, A114 (2012).
2. A. Boyarsky, D. Malyshev, and O. Ruchayskiy, Physics of the Dark Universe **2**, 90 (2013).
3. M. Ackermann *et al.* (FERMI-LAT Collaboration), Phys. Rev. D **88**, 082002 (2013).
4. The Fermi-LAT Collaboration, Phys. Rev. D **91**, 122002 (2015).
5. T. Bringmann, X. Huang, A. Ibarra, S. Vogl, and C. Weniger, J. Cosmol. Astropart. Phys. **7**, 54 (2012).
6. C. Weniger, J. Cosmol. Astropart. Phys. **8**, 7 (2012).
7. E. Tempel, A. Hektor, and M. Raidal, J. Cosmol. Astropart. Phys. **9**, 32 (2012).
8. M. Su and D.P. Finkbeiner, e-print arXiv:1207.7060.
9. W. Buchmüller and M. Garny, J. Cosmol. Astropart. Phys. **8**, 35 (2012).
10. J.-C. Park and S.C. Park, Phys. Lett. B **718**, 1401 (2013).
11. M. Endo, K. Hamaguchi, S. Pei Liew, K. Mukaida, and K. Nakayama, Phys. Lett. B **721**, 111 (2013).
12. V. Schönfelder (COMPTEL Collaboration), Astron. Astrophys. Suppl. **143**, 145 (2000).
13. F.A. Aharonian, S.V. Bogovalov, and D. Khangulyan, Nature **482**, 507 (2012).
14. Z. Malkin, e-print arXiv:1202.6128.
15. G.R. Blumenthal and R.J. Gould, Rev. Mod. Phys. **42**, 237 (1970).
16. J.A. Pons, B. Link, J.A. Miralles, and U. Geppert, Phys. Rev. Lett. **98**, 1101 (2007).
17. S. Zhang, W. Collmar, W. Hermsen, and V. Schönfelder, Astron. Astrophys. **421**, 983 (2004).
18. K. Ferrière, Astrophys. J. **497**, 759 (1998).
19. V.A. Dogiel, H. Inoue, K. Masai, V. Schönfelder, and A.W. Strong, Astrophys. J. **581**, 1061 (2002).

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КОМПТОНІЗАЦІЯ КОСМІЧНОГО МІКРОХВИЛЬОВОГО ВИПРОМІНЮВАННЯ ХОЛОДНИМ УЛЬТРАРЕЛЯТИВІСТСЬКИМ ЕЛЕКТРОН-ПОЗИТРОННИМ ВІТРОМ ТА ПРИРОДА ∼130 ГеВ ЛІНІЙ

Р е з ю м е

В роботі [1] було запропоновано астрофізичне пояснення вузьких гамма-ліній близько 100 ГеВ з області Галактичного центра, спостережених гамма-телескопом Fermi/LAT [2]. Модель [1] базується на комптонівському розсіянні зовнішнього ультрафіолетового/рентгенівського випромінювання холодним ультрарелятивістським електрон-позитронним вітром. Показано, що має з'явитися додаткова широка компонента в МеВ діапазоні від комптонізації космічного мікрохвильового фонового випромінювання. Оцінено основні параметри цієї компоненти і показано, що вона могла бути спостережною МеВ телескопами такими, як CGRO/COMPTEL. Положення джерела GRO J1823-12 близьке до надлишку випромінювання в діапазоні 105–120 ГеВ (регіон 1 [2]), що може бути інтерпретовано як аргумент на користь астрофізичного походження 100 ГеВ ліній.