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Probing the Origin of Cosmic Rays in Cygnus Cocoon Using Ultrahigh-energy Gamma-Ray and Neutrino Observations

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Abstract

Recent ultrahigh-energy gamma-ray observations by the High Altitude Water Cherenkov Observatory up to 100 TeV and LHAASO observatories up to 1.4 PeV energies from the direction of Fermi Large Area Telescope 4FGL source 4FGL J2028.6 + 4110e (Cygnus Cocoon) are indicative of a hadronic origin over a leptonic process for their creation. The IceCube Neutrino Observatory has reported IceCube-201120A, a neutrino event coming from the same direction, suggesting that the Cygnus Cocoon may correspond to one of the most plausible sources of high-energy cosmic rays. The apparent relationship of the neutrino event with the observed ultrahigh-energy gamma rays from the Cygnus Cocoon is investigated in this work to study if it can be explained consistently in hadronic interactions of accelerated cosmic rays with ambient matter. Our findings reveal that leptonic mechanisms, together with pure hadronic mechanisms, make a considerable contribution to the understanding of the total electromagnetic spectrum as well as the observed neutrino event. The estimate of expected muon neutrino events from the Cygnus Cocoon agrees with the one muon neutrino event detected so far in IceCube multiyear observations. Thus, our results are indicative of the potential of the Cygnus Cocoon to be a Galactic cosmic-ray source capable of accelerating at least up to PeV energies.

Unified Astronomy Thesaurus concepts: Cosmic ray sources (328); Cosmic rays (329)

1. Introduction

The Milky Way is known to accelerate cosmic rays with energies up to a few PeV (PeVatrons); however, the origin of Galactic cosmic rays has yet to be proven (Hillas 1984; Berezinskii et al. 1990). Supernova remnants (SNRs) are commonly regarded as the most likely origins of Galactic cosmic rays since they are powerful and abundant enough to sustain the intensity of observed cosmic rays (Baade & Zwicky 1934; Blasi 2013). However, normal conditions make it difficult for SNRs to accelerate particles to PeV energies (Aharonian 2013; Bell et al. 2013). Moreover, there is just no observational evidence to support SNRs as sources of hadrons with energy more than a few tens of TeV (Helder et al. 2012; Aharonian et al. 2019). Supernova explosions tend to cluster in space (within a few parsecs) and time because large OB stars (the progenitors of core-collapse supernovae) are formed in clusters and live short lives (within a few 10^5 yr) (Higdon & Lingenfelter 2005). As a result, Galactic cosmic rays with energy up to PeV are anticipated to be accelerated by overlapping shocks from SNRs and massive stellar winds (referred to as superbubbles; Tenorio-Tagle & Bodenheimer 1988) generated around OB associations (Bykov & Fleishman 1992; Parizot et al. 2004). The energy spectra and radial distribution of the calculated cosmic-ray flux give evidence for particles accelerated to near-PeV energies in large star clusters (Aharonian et al. 2019).

The accelerated cosmic rays in the superbubbles may interact with ambient matter and radiation within the source, producing ultrahigh-energy gamma rays and neutrinos with energies up to PeV. Observations of neutrinos produced in association with ultrahigh-energy gamma rays would unambiguously identify superbubbles as Galactic cosmic-ray PeVatrons. The IceCube collaboration recently announced a candidate track-like neutrino event with an estimated energy of 154 TeV through the standard BRONZE alert procedure (Blaufuss et al. 2019) on 2020 November 20 (IceCube Collaboration 2020; Dzhappuev et al. 2021). The neutrino event is likely linked to an extended gamma-ray source Cygnus Cocoon, which is a superbubble surrounding a region of OB2 massive star formation (IceCube Collaboration 2020). The Carpet−2 experiment reported a 3.1σ (posttrial) excess of atmospheric air showers from the same direction, consistent with a few months' flare in photons over 300 TeV, in temporal correlation with the neutrino event (Dzhappuev et al. 2021). Implication of this observation has been discussed in detail in the results section. This is the first evidence for a neutrino event being correlated with a Galactic object, despite being determined with considerable uncertainty (Dzhappuev et al. 2021).

The Fermi Gamma-Ray Space Telescope's Large Area Telescope (LAT) first identified the Cygnus Cocoon emitting hard, multi-GeV gamma rays in the nearby star-forming area known as Cygnus X (Ackermann et al. 2011). The ARGO experiment first identified it at TeV energies (Bartoli et al. 2014). The High Altitude Water Cherenkov (HAWC) observatory has reported observations of 1–100 TeV gamma rays originating from the Cygnus Cocoon, which may be represented by a power law below 10 TeV and exhibits spectrum softening around 10 TeV (Abeysekara et al. 2020, 2021). The LHAASO collaboration recently reported the discovery of ultrahigh-energy photons with energies up to 1.4 PeV from this location, indicating that the spectrum can extend up to ∼1 PeV (Cao et al. 2021; Li 2021). Amenomori et al. (2021) revealed that gamma-ray sources in the Cygnus area contribute significantly to the Galactic-plane diffuse gamma radiation above 400 TeV. These findings imply that the Cygnus Cocoon may be acting as a Galactic hadronic PeVatron, and could provide significant evidence for understanding the knee of the observed cosmic-ray energy spectrum.

The star-forming regions such as the Cygnus constellation have been proposed as potential sites for cosmic-ray acceleration, as well as gamma-ray and neutrino production (Yang et al. 2019). It has been suggested that the high-energy neutrino flux from the Cygnus Cocoon will be close to the IceCube sensitivity (Yoast-Hull et al. 2017). The detected gamma-ray flux might be both leptonic and hadronic in nature. The HAWC collaboration reported that the observed 1–100 TeV gamma rays from the Cygnus Cocoon were unlikely to be explained by a single electron population emitting gamma rays from GeV to the highest energy via inverse-Compton (IC) emission without its synchrotron radiation exceeding the flux limits set by radio and X-ray studies (Abeysekara et al. 2021). Therefore, a significant contribution in the gamma-ray spectrum above a few TeV is likely to have a hadronic origin for their production. However, the appearance of a cutoff or a break in the measured gamma-ray spectrum at a few TeV is thought to be due to either cosmic-ray leakage from the Cocoon or a cutoff in the cosmic-ray spectrum injected from the source (Abeysekara et al. 2021). Again, the most recent LHASSO observations of ultrahigh-energy gamma rays up to 1.4 PeV from the Cygnus Cocoon significantly disfavored a leptonic origin for their formation and strongly imply acceleration of cosmic rays at energies greater than PeV (Cao et al. 2021). Therefore, the apparent association of the observed neutrino event IceCube-201120A with the measured ultrahigh-energy gamma rays up to the highest energies demands a new explanation for their productions.

Under such circumstances, we would like to examine the apparent link of the neutrino event IceCube-201120A with the observed ultrahigh-energy gamma rays from the Cygnus Cocoon to study whether it can be explained consistently in the framework of hadronic interactions of accelerated cosmic rays with ambient matter. We will also investigate the possibility of a leptonic origin contribution to the total gamma-ray spectra, in addition to a hadronic origin, taking into account IceCube's nondetection of multiple neutrino events. We would also like to inspect the maximum energy that a cosmic-ray particle can achieve in the Cygnus Cocoon.

The following is the article's structure: The next section describes the method for evaluating gamma-ray and neutrino fluxes from the Cygnus Cocoon. Section 3 shows numerical estimates of the fluxes of multiwavelength electromagnetic (EM) spectral energy distribution (SED) and high-energy neutrinos produced by the Cygnus Cocoon. The results are also discussed in the same section. Finally, we will conclude in Section 4.

2. Methodology

It can be generally assumed that the electrons and protons are coaccelerated via the diffusive shock acceleration mechanism in the interacting winds created by the collective activity of massive stars in the Cygnus Cocoon. We can assume that a fraction of the stellar wind energy, η_e, may be used to accelerate electrons and a fraction, η_p, can be used to accelerate hadrons (Bednarek 2007).

In this case, we consider a broken power-law energy distribution of shock-accelerated electrons with spectral indices α_1 and α_2 before and after the spectral break at Lorentz factor γ_b, as illustrated below (Katarzyński et al. 2001):

$$N_e(\gamma_e) = K_e \gamma_e^{-\alpha_1} \text{ if } \gamma_{e,\min} \leqslant \gamma_e \leqslant \gamma_b$$
$$= K_e \gamma_b^{\alpha_2-\alpha_1}\gamma_e^{-\alpha_2} \text{ if } \gamma_b < \gamma_e \leqslant \gamma_{e,\max}, \quad (1)$$

where K_e represents the normalization constant, which is related with the available stellar wind power (L_w) as given below:

$$\eta_e \frac{L_w}{4\pi r^2 v_w} = m_e c^2 \int_{\gamma_{e,\min}}^{\gamma_{e,\max}} \gamma_e N_e(\gamma_e) d\gamma_e, \quad (2)$$

where $\gamma_e = E_e/m_e\, c^2$ represents the Lorentz factor of electrons of energy E_e, r is the radius of the Cygnus Cocoon, and v_w is a typical stellar wind velocity. For a radiative cooling break in a uniform magnetic field B, the electron distribution breaks in its index by one power (i.e., $\Delta\ \alpha = \alpha_2 - \alpha_1 \approx 1$) above the spectral break Lorentz factor γ_b (Longair 1994).

The low-energy component of the EM SED extending from radio to X-ray energies generated in the Cygnus Cocoon is represented by synchrotron radiation of primary accelerated electrons, which is estimated here using the methodology given by Böttcher et al. (2013). The IC scattering of primary accelerated electrons with target photons contributes significantly to the observed EM spectrum in the MeV to GeV ranges and may be estimated using the formulas presented in Blumenthal & Gould (1970). Here, we consider four target radiation fields following Ackermann et al. (2011) for gamma-ray generation via IC scattering, including synchrotron photons, strong stellar light fields around Cyg OB2 and NGC 6910 (a star cluster in the neighborhood of OB2), and a more diffuse dust radiation field over the whole Cocoon. The Bremsstrahlung scattering of primary accelerated electrons with ambient matter of density $n_{\rm H}$ is found to explain the observed gamma-ray spectrum in the GeV to few TeV energy band and may be estimated by following Blumenthal & Gould (1970).

The cosmic-ray (protons) production spectrum is also expected to follow a power law (Malkov & Drury 2001)

$$\frac{dn_p}{dE_p} = K_p E_p^{-\alpha_p}, \quad (3)$$

where E_p denotes the energy of the cosmic-ray proton, α_p is the spectral index, and the proportionality constant is K_p, which may be derived by using the fraction of stellar wind energy carried by cosmic-ray protons as follows:

$$\eta_p \frac{L_w}{4\pi r^2 v_w} = \int_{E_{p,\min}}^{E_{p,\max}} E_p \frac{dn_p}{dE_p} dE_p, \quad (4)$$

where $E_{p,\min}$ and $E_{p,\max}$ denote the minimum and maximum energies of accelerated cosmic-ray protons, respectively.

The interaction of shock-accelerated cosmic-ray protons with ambient matter (protons) of density $n_{\rm H}$ can explain the high-energy gamma-ray emission from the Cygnus Cocoon. Such hadronic (pp) interaction produces neutral and charged pions, which decay to create high-energy gamma rays and neutrinos, respectively. To estimate the high-energy gamma rays and neutrino emissivities (Q_γ^{pp} & Q_ν^{pp} respectively) produced in hadronic interactions (pp) in the Cygnus Cocoon, we follow Kelner et al. (2006) and Banik & Bhadra (2017, 2019). The associated differential flux of high-energy gamma rays and muon neutrinos reaching Earth from the Cygnus Cocoon may be represented as

$$\frac{d\Phi_{\gamma/\nu_\mu}}{dE_{\gamma/\nu}} = \zeta \frac{V}{4\pi d^2} Q^{pp}_{\gamma/\nu}(E_{\gamma/\nu}), \quad (5)$$

where ζ is a constant equal to 1 for gamma rays and equal to 1/3 for muon neutrinos due to neutrino oscillation, $V = \frac{4}{3}\pi r^3$ represents the volume of the emission region, and d is the distance between the Cygnus Cocoon and the Earth. The number of expected muon neutrino events in the IceCube detector in time t may be computed using the following formula:

$$N_{\nu_\mu} = t \int_{E_{\nu,\min}}^{E_{\nu,\max}} A_{\rm eff}(E_\nu). \frac{d\Phi_{\nu_\mu}}{dE_\nu} dE_\nu, \quad (6)$$

where A_{eff} is the effective area of the IceCube detector (IC86) at the decl. of the source (IceCube Collaboration 2021). We can choose $E_{\nu,\rm min} \approx 30$ TeV, which is in good agreement with the effective energy threshold of the IceCube detector for astrophysical neutrinos (Taboada 2016).

3. Results and Discussion

The Cygnus Cocoon is situated at R.A. 307°.17 and decl. 41°.17 (J2000; IceCube Collaboration 2020). It has an angular size of around 2°.1, corresponding to a radius of $r = 55$ pc at a distance of $d = 1.4$ kpc from Earth (Abeysekara et al. 2021). The Cygnus Cocoon comprises of two star clusters, Cyg OB2 and NGC 6910, with total wind power estimates of $(2-3) \times 10^{38}$ erg s^{-1} and $(1-1.5) \times 10^{36}$ erg s^{-1}, respectively (Ackermann et al. 2011). Here, we consider a typical stellar wind with velocity $v_w = 10^3$ km s^{-1} (Ackermann et al. 2011) and wind power $L_w = 3 \times 10^{38}$ erg s^{-1} to estimate stellar wind energy density.

The IceCube neutrino observatory has reported a neutrino event IceCube-201120A, which is likely to be associated to the Cygnus Cocoon. The Carpet−2 experiment observed an excess of gamma-ray events consistent with a few months' flare in photons above 300 TeV from the direction of the Cygnus region, in temporal and spatial coincidence with the IceCube neutrino alert (Dzhappuev et al. 2021). As the gamma-ray emission from the Cocoon (the radius ∼55 pc) cannot vary on a timescale of months, this neutrino event is more likely to be due to any compact source within the Cocoon rather than the diffused emission. Therefore, if this event is truly related with the few months' gamma-ray flare, it cannot be used to limit hadronic gamma-ray emission from the Cocoon. However, the neutrino event may not be linked to such a flare because no excess GeV–TeV gamma-ray flux was measured from the Cygnus region during the neutrino arrival period by Fermi-LAT and HAWC (Garrappa et al. 2020; Ayala & HAWC Collaboration 2020).

Recently, the LHAASO observatory detected a gamma-ray flux of 0.54 (0.10) Crab Units (CU) at 100 TeV (CU, the Crab Nebula flux at 100 TeV; 1 CU = 6.1×10^{-17} photons TeV^{-1} cm^{-2} s^{-1}) from the direction of the source LHAASO J2032 + 4102 (Cygnus Cocoon) when only half of its KM2A detectors were operational (Cao et al. 2021). The LHAASO observatory found 45 on-source events (with 6.7 number of background events) with energies above 100 TeV up to 1.4 PeV during an exposure period of 2648.2 hr from the direction of the Cygnus Cocoon (Cao et al. 2021). We estimated the corresponding gamma-ray flux seen by LHAASO from the Cygnus Cocoon by assuming a power-law gamma-ray spectrum of $f_\gamma = N_0 E^{-\Gamma}$ with a photon index of $\Gamma \approx 2.7$ in the energy range of 100 TeV to 1.4 PeV. The normalization constant N_0 of the observed gamma-ray flux from the Cygnus Cocoon by LHAASO may be computed as (Aharonian et al. 2020)

$$S_\gamma = \epsilon T_{\rm ex} \int_{100\ TeV}^{1.4 PeV} A^\gamma_{\rm eff} f_\gamma \, dE_\gamma, \quad (7)$$

where S_γ represents the number of gamma-ray signal events in the LHAASO detector, $A^\gamma_{\rm eff}$ denotes the effective area when only half of its KM2A detectors were operational (Aharonian et al. 2021), and $T_{\rm ex}$ represents the corresponding exposure time (Cao et al. 2021) for the Cygnus Cocoon. Here, $\epsilon = 0.68$ is the fraction of observed event counts within the angular resolution of the instrument (He et al. 2019). The combined gamma-ray spectra from GeV to highest energies (1.4 PeV) from the Cygnus Cocoon as observed by Fermi-LAT (Ackermann et al. 2011; Astiasarain et al. 2021), ARGO (Bartoli et al. 2014), HAWC (Abeysekara et al. 2021), and LHAASO (Cao et al. 2021; Li 2021) observatories indicate a hadronic origin for their generation (Abeysekara et al. 2021; Cao et al. 2021).

The likelihood of a leptonic origin contribution to the overall gamma-ray spectra, in addition to a hadronic origin, is examined below, taking into consideration IceCube's non-detection of multiple neutrino events from the Cygnus Cocoon.

3.1. Pure Hadronic Origin

We have estimated the gamma-ray flux produced in the hadronic interaction (pp) of a single population of accelerated cosmic rays (protons) with the ambient protons within the astronomical object Cygnus Cocoon. Because the Cygnus area contains a massive molecular cloud complex with a total mass of $8 \times 10^6 M_\odot$ (Ackermann et al. 2012), the interstellar gas density should be more than 10 cm^{-3} (Bartoli et al. 2014). To explain the observed EM SED, we choose an ambient matter density of $n_{\rm H} = 30$ cm^{-3} in the area, as suggested by H I and H II observations (Abeysekara et al. 2021). Here, we adopt a magnetic field of $B = 20$ μG as inferred from pressure balance with the gas throughout the Cygnus Cocoon region (Ackermann et al. 2011).

We compared the acceleration timescale of a proton with its energy loss timescale in pp interaction, diffusion timescale, and the age of the Cocoon ($t_{\rm age} \sim 2$ Myr) to understand the maximum achievable energy by a cosmic-ray particle within the Cocoon. The timescale of acceleration of cosmic-ray protons can be represented as $\left(t_{\rm acc} = \frac{E_p}{\xi_p eBc}\right)$, where ξ_p ($\leqslant 1$) is the proton acceleration coefficient. The energy loss timescale for protons in pp interaction can be written as $t_{pp} = \frac{1}{k_{pp}\sigma_{pp} n_H c}$, where $k_{pp} = 0.45$ and σ_{pp} represent the inelasticity (Gaisser 1990) and the interaction cross section (Kelner et al. 2006), respectively. The diffusion timescale can be represented by $t_{\rm diff} = \frac{r^2}{D_{\rm diff}}$ (Bednarek 2007), where $D_{\rm diff} = D_0 \left(\frac{E_p}{10\ \rm GeV}\right)^\delta$ (Giuliani et al. 2010; Berezinskii et al. 1990) denotes the diffusion coefficient of accelerated protons. We may choose $D_0 = 1.2 \times 10^{27}$ cm^2/s as the diffusion coefficient at 10 GeV

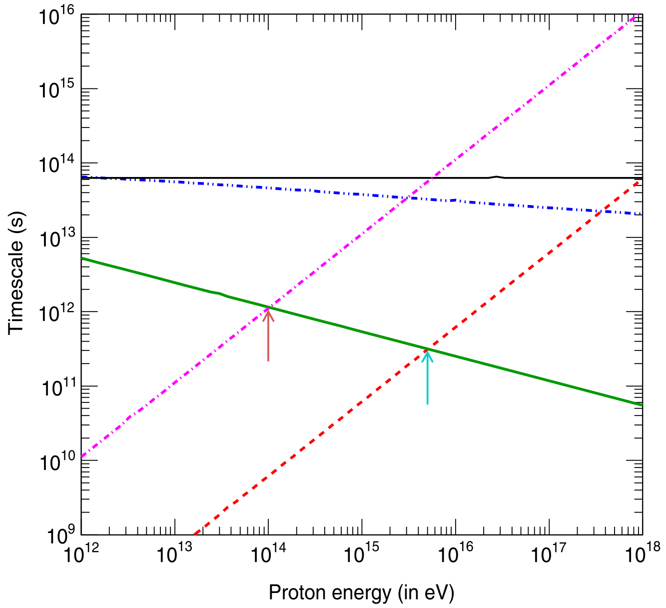

Figure 1. The estimated relevant timescales for protons. The red dashed and magenta dashed–single-dotted lines represent the acceleration timescales with $\xi_p = 9 \times 10^{-5}$ and 5×10^{-7} respectively. The blue dashed–double-dotted and green dashed–triple-dotted lines denote the energy loss timescale for protons in *pp* interaction and diffusion timescale respectively. The black continuous line indicates the lifetime of the Cocoon. The points, as indicated by the cyan and brown arrows, represent the maximum achievable energy by a cosmic-ray proton with $\xi_p = 9 \times 10^{-5}$ and 5×10^{-7} respectively.

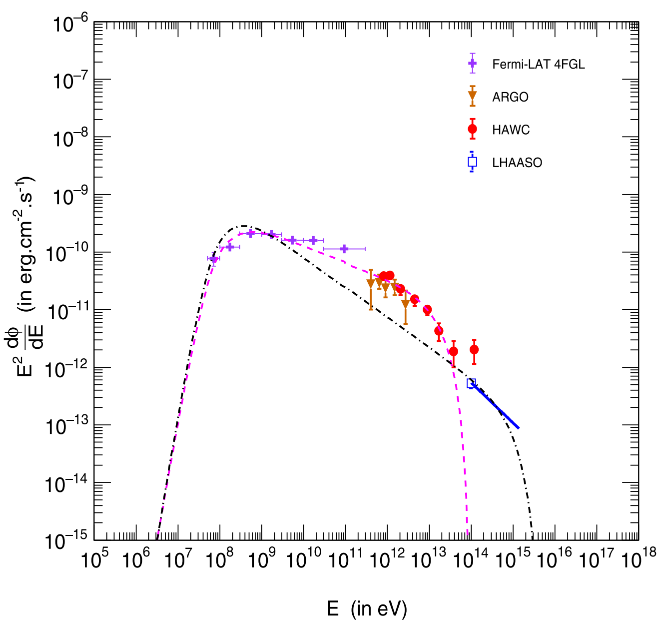

Figure 2. The estimated differential EM SED reaching Earth from the Cygnus Cocoon in the pure hadronic origin scenario. The black dashed–dotted and magenta dashed lines represent the EM spectrum produced with $\eta_p = 100\%$, $\alpha_p = -2.6$, and $E_{p,\max} = 5 \times 10^{15}$ eV and $\eta_p = 1.6\%$, $\alpha_p = -2.35$, and $E_{p,\max} = 10^{14}$ eV, respectively. The blue continuous line represent our estimated gamma-ray flux limit detected by LHAASO.

energy since the dense gaseous medium has a slower diffusion than the galactic medium ($\approx 10^{28}$ cm^2/s in our Galactic medium) (Berezinskii et al. 1990; Aharonian & Atoyan 1996). We have taken into account $\delta = 0.33$, as recently found by the Alpha Magnetic Spectrometer when measuring the boron to carbon flux ratio in cosmic rays (Aguilar et al. 2016). The

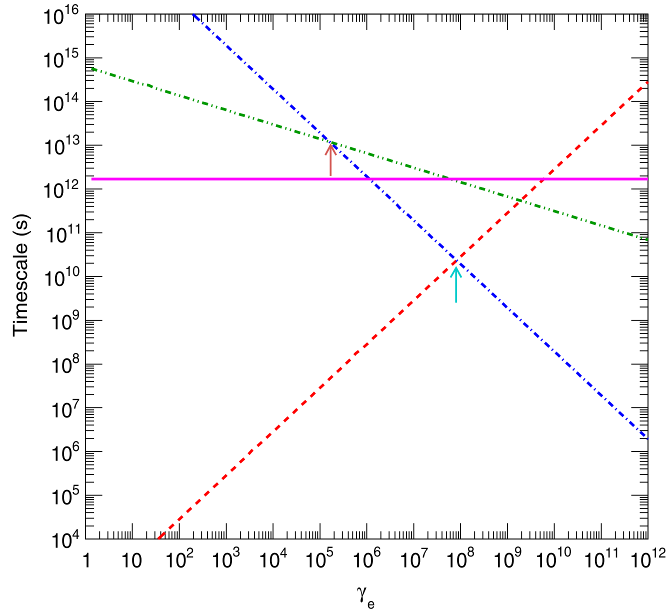

Figure 3. The estimated relevant timescales for electrons. The red dashed and blue dashed–single-dotted lines represent the acceleration timescale of the electron with $\xi_e = 10^{-5}$ and synchrotron cooling timescale, respectively. The green dashed–double-dotted and magenta dashed–triple-dotted lines denote the diffusion and advection timescales, respectively. The points, as indicated by the cyan and brown arrows, represent the maximum achievable Lorentz factor and spectral break Lorentz factor of an electron, respectively.

aforementioned timescales of relativistic protons as functions of proton energy are displayed in Figure 1 (also see Bednarek 2007). By comparing the acceleration timescale of a proton with its diffusion timescale (e.g., Bednarek 2007), we found that hadrons can be accelerated up to 5×10^{15} eV (or 10^{14} eV) within the Cocoon with an acceleration coefficient of $\xi_p = 9 \times 10^{-5}$ (or 5×10^{-7}).

To match the observed gamma-ray spectrum, we first consider a primary cosmic-ray production spectrum obtained by assuming an acceleration efficiency of $\eta_p = 100\%$ of cosmic-ray protons with a spectral index of $\alpha_p = -2.6$, and the maximum energy of $E_{p,\max} = 5 \times 10^{15}$ eV. According to our findings, an estimated gamma-ray flux based on a single power-law distribution of accelerated cosmic rays cannot properly explain the observed overall gamma-ray spectrum up to energies of 1.4 PeV. This is mostly due to a spectral break in the gamma-ray spectrum around 10 TeV energy, which has been seen in both ARGO and HAWC detector studies.

When we consider $\eta_p = 1.6\%$, i.e., the portion of the stellar wind energy carried by cosmic-ray protons with a spectral index of $\alpha_p = -2.35$ and a maximum achievable energy of $E_{p,\max} = 10^{14}$ eV, the observed gamma-ray spectrum can be reproduced well from the GeV to a few tens of TeV energy range. However, it was unable to explain the reported PeV gamma-ray flux by the LHAASO detector. The estimated differential gamma-ray flux reaching the Earth from the Cygnus Cocoon for two stated scenarios is displayed in the Figure 2 along with the observations.

In the next section, we have investigated whether viable leptonic processes, in conjunction with pure hadronic mechanisms, can explain the observed spectrum of gamma rays, as well as the reported neutrino event from the Cygnus Cocoon.

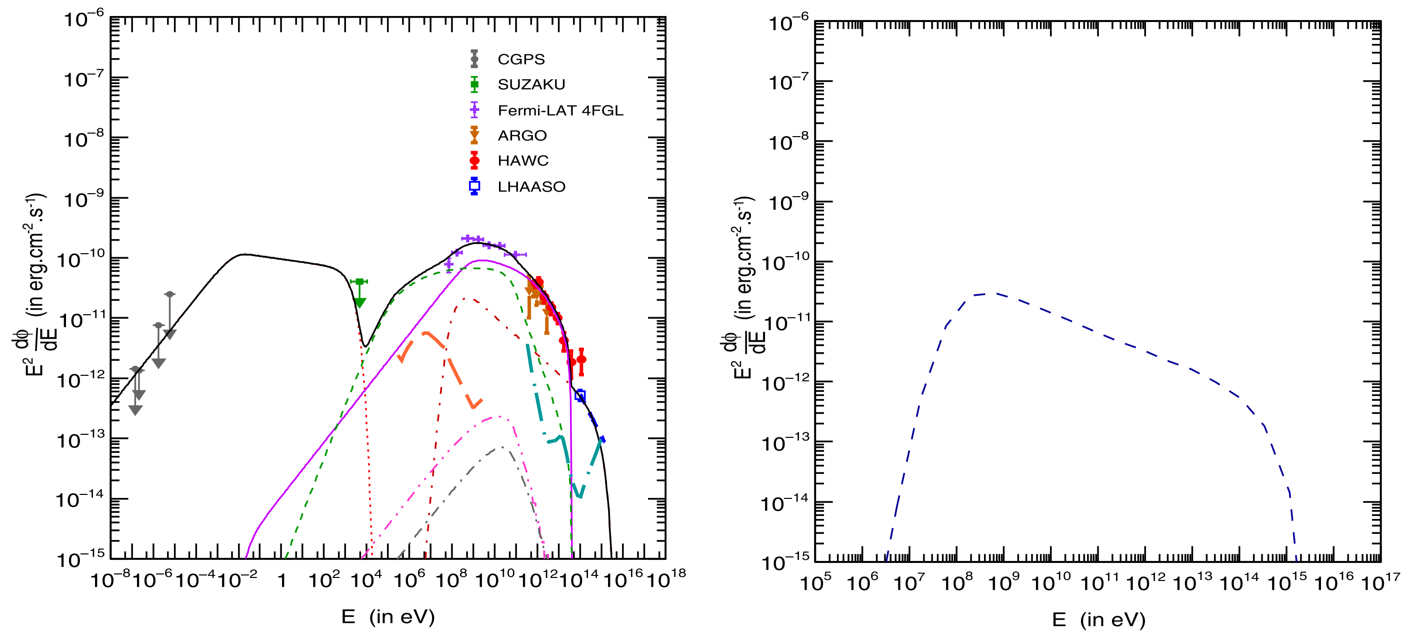

Figure 4. Left: the estimated differential EM SED reaching Earth from the Cygnus Cocoon in the leptohadronic origin scenario. The red dotted and green small-dashed lines represent the EM spectrum produced by synchrotron emission and Bremsstrahlung scattering of primary relativistic electrons in ambient matter, respectively. The EM spectrum produced by IC scattering of relativistic electrons with starlight fields around NGC 6910 and Cyg OB2, as well as a dust radiation field, is denoted by the gray long-dashed–single-dotted, magenta long-dashed–double-dotted, and violet long-dashed–triple-dotted lines, respectively. The gamma-ray flux created in *pp* interactions between relativistic protons and ambient protons is indicated by the brown small-dashed–single-dotted line. The black continuous line shows the estimated overall differential multiwavelength EM SED coming from the Cygnus Cocoon. The cyan very-long-dashed–single-dotted and orange very-long-dashed lines indicate the detection sensitivity of the LHAASO and e-ASTROGAM detectors for one years of observation, respectively. The blue long-dashed line represents our estimated gamma-ray flux limit detected by LHAASO. Right: the estimated corresponding all-flavor neutrino flux reaching the Earth from the Cygnus Cocoon.

3.2. Leptohadronic Origin

The source is thought to accelerate both electrons and protons at the same time. The acceleration timescale of electrons is expressed similarly to that of protons, but with $\xi_e \leqslant 1$ as the acceleration coefficient. To estimate the diffusion timescale, we use $D_{\rm diff} = 1.2 \times 10^{27}\left(\frac{E_e}{10\ \rm GeV}\right)^{0.33}$ cm^2/s as the diffusion coefficient for electrons, which is the same as that for protons at 10 GeV energy. The advection timescale can be estimated as $t_{\rm adv} = r/v_w$ (Bednarek & Sitarek 2007). The maximum electron Lorentz factor ($\gamma_{e,\rm max}$) was calculated by matching the acceleration timescale with the synchrotron energy loss timescale $\left(t_{\rm cool} = \frac{3mc}{4u_B\sigma_T\gamma_e}\right)$ and was found to be 8×10^7 with an acceleration coefficient of $\xi_e = 10^{-5}$. Here, $u_B = \frac{B^2}{8\pi}$ represents the magnetic field energy density and σ_T is the Thomson scattering cross section. The synchrotron cooling timescale begins to take precedence over the diffusive timescale, i.e., the average time spent by electrons with energy E_e inside the Cocoon region, at Lorentz factor 1.7×10^5 as shown in Figure 3, which can be regarded as the spectral break Lorentz factor γ_b.

We consider a broken power-law distribution of accelerated primary electrons with spectral indices of $\alpha_1 = 2.1$ and $\alpha_2 = 3.1$ before and after the spectral break at the Lorentz factor $\gamma_b = 1.7 \times 10^5$, derived by assuming a fraction of wind energy $\eta_e = 9\%$ carried by the electrons. The synchrotron emission of the accelerated electrons has been computed and compared to multiwavelength observations of the Cygnus Cocoon from radio to X-ray energies. The IC scattering of primary relativistic electrons with synchrotron photons comoving within the source is found to have no substantial contribution to the observed EM spectrum from the source at energies ranging from MeV to TeV. A significant contribution to the observed EM spectrum in the MeV to a few tens of TeV energy range is found to be produced by IC scattering of primary relativistic electrons with strong starlight fields around Cyg OB2 and NGC 6910 (a star cluster in the neighborhood of OB2), and a more diffuse dust radiation field over the entire Cocoon. Furthermore, we have found that the gamma-ray flux produced by Bremsstrahlung scattering of primary relativistic electrons in ambient matter with a density of $n_{\rm H} = 30\ \rm cm^{-3}$ may contribute significantly to the measured gamma-ray energies ranging from MeV to TeV from the source.

The interactions of relativistic primary cosmic rays with ambient protons in the source can contribute significantly to EM SED above 100 TeV energies, as detected by the LHAASO observatory, as well as generate high-energy neutrinos. The required fraction of star wind energy carried by the accelerated primary protons is determined to be $\eta_p = 8\%$ with the best-fitting spectral slope of $\alpha_p = -2.4$ and the maximum attainable energy $E_{p,\rm max} \simeq 5 \times 10^{15}$ eV. The left panel of Figure 4 shows the estimated differential gamma-ray spectra escaping from the Cygnus Cocoon along with the different satellite and ground-based observational data. Using Equation (7) and the model-estimated gamma-ray flux from the Cygnus Cocoon, we again computed the predicted gamma-ray signal events in the LHAASO detector from the source and found that they were compatible with the observations.

The estimated neutrino flux from the Cygnus Cocoon reaching Earth is displayed in the right panel of the Figure 4. The expected muon neutrino event in the IceCube detector from the Cygnus Cocoon is estimated to be a roughly $N_{\nu\mu} = 0.65$ event above 30 TeV energy in 10 yr using Equation (6). Because a possible contribution to the event rates due to interactions of tau neutrinos that create muons with

Table 1
Model Fitting Parameters for Cygnus Cocoon According to Leptohadronic Model

Parameters	Values
L_w (in erg s^{-1})	3×10^{38}
v_w (in km s^{-1})	10^3
B (in μG)	20
α_1	−2.1
α_2	−3.1
γ_b	1.7×10^5
$\gamma_{e,\min}$	1
$\gamma_{e,\max}$	8×10^7
η_e	9%
$n_{\rm H}$ (in cm^{-3})	30
α_p	−2.4
$E_{p,\min}$ (in eV)	10^9
$E_{p,\max}$ (in eV)	5×10^{15}
η_p	8%

a branching ratio of 17.7% was not addressed, the estimated number of neutrino events is conservative (Ansoldi et al. 2018; Banik et al. 2020). As a result, the total muon-like neutrino events may be computed as $N_\mu^{\rm like} = N_\mu + 17.7\% \times N_\mu$, resulting in a 0.77 event. Our estimate of expected muon neutrino events is consistent with the only one muon neutrino event reported so far from the Cocoon direction in IceCube multiyear observations. The model fitted parameters are displayed in Table 1.

4. Conclusion

The observed 1–100 TeV gamma rays from the Cygnus Cocoon are unlikely to be explained by a single electron population emitting gamma rays from GeV to the highest energy via IC and Bremsstrahlung emission without exceeding the flux limits established by radio and X-ray studies. Our findings show that the combined gamma-ray spectra from GeV to maximum energies (1.4 PeV) from the Cygnus Cocoon as reported by Fermi-LAT, ARGO, HAWC, and LHAASO observatories cannot be explained by pure hadronic (*pp*) interactions of relativistic cosmic rays with ambient matter. Our results suggest that leptonic processes, in combination with pure hadronic mechanisms, are necessary to consistently represent the complete EM spectrum. Particularly, the detected gamma-ray flux in sub-PeV energies by LHAASO is found to be best explained by hadronic interaction of cosmic rays, which originated in the Cygnus Cocoon, with ambient matter. The single muon neutrino event detected so far from the Cocoon direction in IceCube multiyear data agrees with our estimate of expected muon neutrino events. Thus, the Cygnus Cocoon might be one of the long-suspected Galactic PeVatrons, capable of accelerating cosmic rays with energies at least up to a few PeV, providing strong evidence for the origin of knee in the observed cosmic-ray energy spectrum. Future gamma-ray telescopes with better sensitivity than current generation gamma-ray telescopes, such as e-ASTROGAM (de Angelis et al. 2018), CTA (Ong 2017), and LHAASO (complete operational mode; Liu et al. 2017), and future neutrino telescopes IceCube-Gen2 (Aartsen et al. 2021) and KM3NeT (Aiello et al. 2019) with better sensitivities may offer a clearer understanding of the physical origin of gamma rays and neutrino emission.

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