universe

MDPI

Communication

Influence of Extragalactic Magnetic Fields on Extragalactic Cascade Gamma-Ray Emission

Anna Uryson

Lebedev Physical Institute of Russian Academy of Sciences, Moscow 119991, Russia; uryson@sci.lebedev.ru

Abstract: We discuss the influence of extragalactic magnetic fields on the intensity of gamma-ray emission produced in electromagnetic cascades from ultra-high energy cosmic rays propagating in extragalactic space. Both cosmic rays and cascade particles propagate mostly out of galaxies, galactic clusters, and large-scale structures, as their relative volume is small. Therefore, their magnetic fields weakly affect emission produced in cascades. Yet, estimates of this influence can be useful in searching for dark matter particles when components of extragalactic gamma-ray background should be known, including cascade gamma-ray emission. To study magnetic field influence on cascade emission, we calculated cosmic particle propagation in fields of ~10^{-6} and 10^{-12} G (the former is typical inside galaxies and clusters and the latter is common in voids and outside galaxies and clusters). The calculated spectra of cascade gamma-ray emissions are similar in the range of ~10^{7}–10^{9} eV, so analyzing cascade emission in this range it is not necessary to specify models of an extragalactic magnetic field.

Keywords: cosmic rays; electromagnetic cascades; extragalactic magnetic field; extragalactic diffuse gamma-ray background; dark matter

check for updates

Citation: Uryson, A. Influence of Extragalactic Magnetic Fields on Extragalactic Cascade Gamma-Ray Emission. *Universe* **2022**, *8*, 569. https://doi.org/10.3390/universe8110569

Academic Editors: Daniele Fargion and Maxim Y. Khlopov

Received: 2 September 2022
Accepted: 27 October 2022
Published: 29 October 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Copyright: © 2022 by the author. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Cosmic rays (CR) at ultra-high energies (UHE) $E > 4 \times 10^{19}$ eV are evidently of extragalactic origin. Propagating in space, they interact with cosmic microwave background (CMB), and radio emission via reactions: $p + \gamma_r \rightarrow p + \pi^0$, $p + \gamma_r \rightarrow n + \pi^+$. Pions and muons decay via $\pi^0 \rightarrow \gamma + \gamma$, $\pi^+ \rightarrow \mu^+ + \nu_\mu$, $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$ and neutrons decay producing p, e^-, and $\bar{\nu}_e$. Gamma quanta, electrons, and positrons are the particles which generate electromagnetic cascades in the interaction with CMB and radio background emission along with extragalactic background light (EBL): $e + \gamma_b \rightarrow e' + \gamma'$ (IC scattering) and $\gamma + \gamma_b \rightarrow e^+ + e^-$ (pair production). Other reactions give a minor contribution to electromagnetic cascades. The development of the electromagnetic cascades in the universe is described in [1–6].

In addition to the processes above, cascade electrons lose energy generating synchrotron radiation in the extragalactic magnetic field (EGMF), which quanta take part in IC scattering. This process affects the cascade process. The value of EGMF that weakly violates cascade development is estimated in [7]: $B < 10^{-9}$ G.

EGMF is inhomogeneous, varying considerably in field strength: magnetic fields are B~10^{-6} G inside and near galaxies, in filaments and sheets fields are B~10^{-9}–10^{-7} G, and fields in voids are $B < 10^{-11}$ G [8]. An experimental indication of EGMF is analyzed in, e.g., [9–12].

In this paper the EGMF effect on the intensity of diffuse cascade gamma quanta is discussed. It could be important searching dark matter (DM) particles, in which the study of any excess of gamma-ray background intensity is analyzed. The reason is that gamma quanta arise in decays of products of DM particle annihilation (see e.g., [13] and ref. therein). Thus, the contribution of various components to the extragalactic background emission should be known, including cascade gamma-rays.

Regarding of the problem of components of extragalactic background emission in EGMF of various values, other models of gamma-ray production by UHECRs were also proposed [14–17]. In the model [14–16], it is suggested that UHE neutrinos born in UHECR interactions in extragalactic space interact with neutrinos in DM galactic halos and produce high-energy gamma-rays via the chain of reactions. Another possibility is that UHECRs are radioactive nuclei, the decay of which gives rise to electrons and consequent synchrotron gamma-rays [17]. However, analyzing the contribution of these processes in gamma-ray emission is beyond the scope of this paper.

At present, the structure and value of the EGMF is unclear. We suppose the EGMF to be uniform, its strength being a model parameter, and discuss cases B~10^{-6} and $B \leq 10^{-12}$ G.

The intensity of cascade gamma-rays was computed with the publically available code TransportCR [18], that simulates the propagation of UHE CRs and cascade particles.

We obtain that in the energy range of ~10^{7}–10^{9} eV, diffuse cascade emission is similar in the EGMF with $B = 10^{-6}$ G and $B \leq 10^{-12}$ G. Thus, analyzing diffuse cascade gamma-ray intensity at these energies specific to EGMF models is not necessary.

In the paper, we use "photons" for particles of background emission, "quanta" for those produced in interaction with the cosmic background and synchrotron process, and "electrons" for both electrons and positrons.

2. Model

The model assumptions concern UHE CRs and their sources, extragalactic background emission, and EGMF structure and value.

We assume that CR sources are evidently of extragalactic origin, their sources being point-like objects, which are active galactic nuclei (AGN). Particle acceleration is connected with supermassive black holes in galactic centers, so AGNs possibly can be UHECR sources regardless of their type and distance [19,20]. We suppose that CRs are accelerated on shock fronts in the vicinity of supermassive black holes (e.g., in jets). This acceleration mechanism produces exponential injection spectra $\propto E^{-\alpha}$, with the spectral index $\alpha \approx 2.2$–2.5 [21–24]. Choosing the value of α, we use results [24]. In this paper, CR data, including UHECR contribution to the extragalactic gamma-ray and neutrino backgrounds are described, varying values of the injection spectral index α and exploring cosmological evolution of astrophysical objects where CRs possibly can be accelerated to UHE. Following [24], we adopt in the model that $\alpha = 2.2$.

The next question is supermassive black hole evolution. It is unclear, and in calculation we use the evolution of blue Lacertae objects (BL Lac), which are one of the AGN types. The reason is that the bulk of CR data are described with it [24]. BL Lac's are located at distances corresponding to red shifts $z \approx 0.001$–5.

We assume that UHE CRs consist of protons.

Extragalactic background emissions are considered in the following way: The CMB has Planck energy distribution with the mean value $\varepsilon_r = 6.7 \times 10^{-4}$ eV. The mean photon density is $n_r = 400$ cm^{-3}. The background radio emission has parameters from the model of the luminosity evolution for radio galaxies [25]. The EBL parameters are taken from [26].

We suppose the EGMF to be uniform, its strength being a model parameter, and calculate cascade gamma-ray intensity when B~10^{-6} and $B \leq 10^{-12}$ G.

Under these assumptions we compute the cascade gamma-ray intensity with the code TransportCR [18], simulating particle propagation in extragalactic space.

3. Results and Discussion

Calculated gamma-ray spectra near the Earth in the fields of 10^{-6} and 10^{-12} G are shown in Figure 1. The spectra when $B < 10^{-12}$ G coincide with that for $B = 10^{-12}$ G, and are not shown in the figure. Varying parameters of the EBL-model [26], the effect on the spectra is minor.

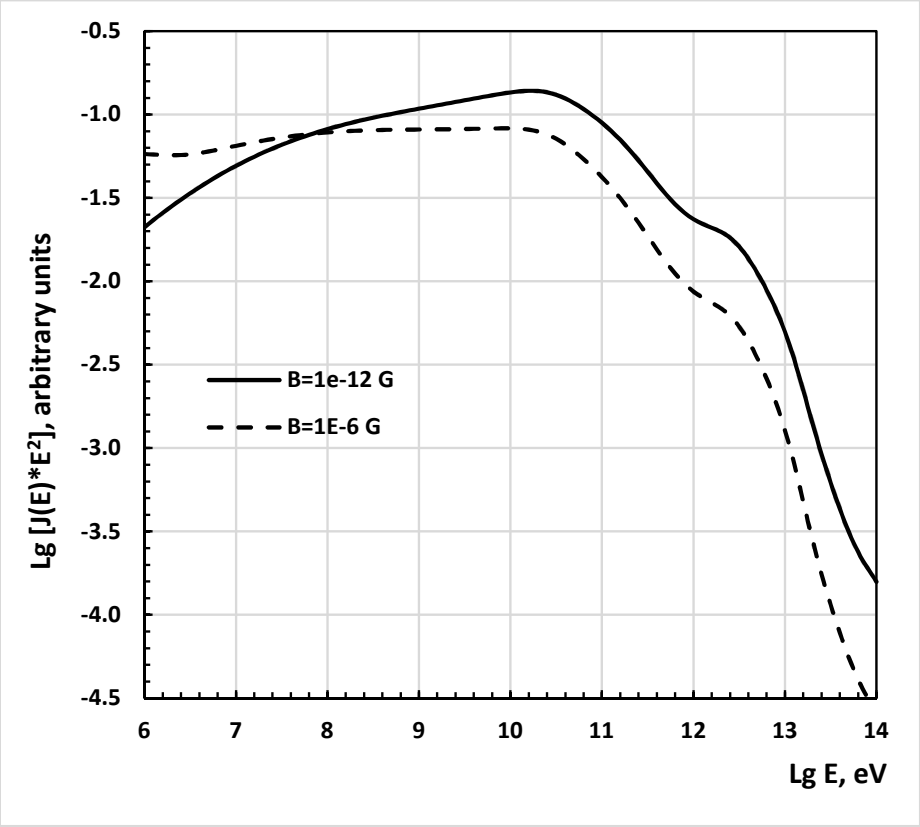


Figure 1. The spectra near the Earth of diffuse cascade gamma-rays produced by UHE protons in the extragalactic magnetic field B of 10^{-6} and 10^{-12} G. The spectra when EGMF is $B < 10^{-12}$ G and $B = 10^{-12}$ G coincide and are not shown in the figure.

Now, we discuss reasons for the difference between the spectra. For a quick rough estimate, we use the expression for the energy at which spectral distribution of the synchrotron emission of a single electron moving in the magnetic field has the maximum (see e.g., [27])

$$E_{\mathrm{s\,max}} = 1.9{\cdot}10^{-20}\, H_{\mathrm{tr}}(E_{\mathrm{eV}})^2 \quad (1)$$

where H_{tr} is the component of the field (in G) perpendicular to the electron velocity, E_{eV} is the electron energy in eV (we discuss here only the energy of maximum $E_{\mathrm{s\,max}}$ as the flux of the synchrotron emission decreases with energy: it is several times lower at energies ≈ 10 times higher than $E_{\mathrm{s\,max}}$). Synchrotron emission transfers electron energy in low-energy gamma quanta: using (1), in the EGMF of 10^{-12}, 10^{-6} G, an electron at the energy of 10^{14} eV produces a bulk of quanta at $E_{\mathrm{s\,max}} = 1.9{\cdot}10^{-4}$ and $1.9{\cdot}10^{2}$ eV, respectively. The higher the field, the larger part of electron energy is outlaid on low-energy synchrotron quanta, thus the smaller part of electron energy is spent cascading gamma-rays. As a result in the range of 10^{8}–10^{14} eV, the gamma-ray intensity calculated with $B = 10^{-6}$ G is lower than that with 10^{-12} G. At energies lower than 10^{8} eV, synchrotron quanta provides an excess of gamma-rays: the larger the field, the higher the excess. Thus, at energies $E < 10^{8}$ eV, the curve with $B = 10^{-6}$ G lies above the one with $B = 10^{-12}$ G.

The energy value at which curves in Figure 1 intersect is governed by location of UHECR sources. This is illustrated in Figure 2, where the ratio R of cascade gamma-ray intensity with $B = 10^{-6}$ G to that with $B = 10^{-12}$ G is shown. The $\log R = 0$ ($R = 1$) corresponds to the intersection of curves in Figure 1.

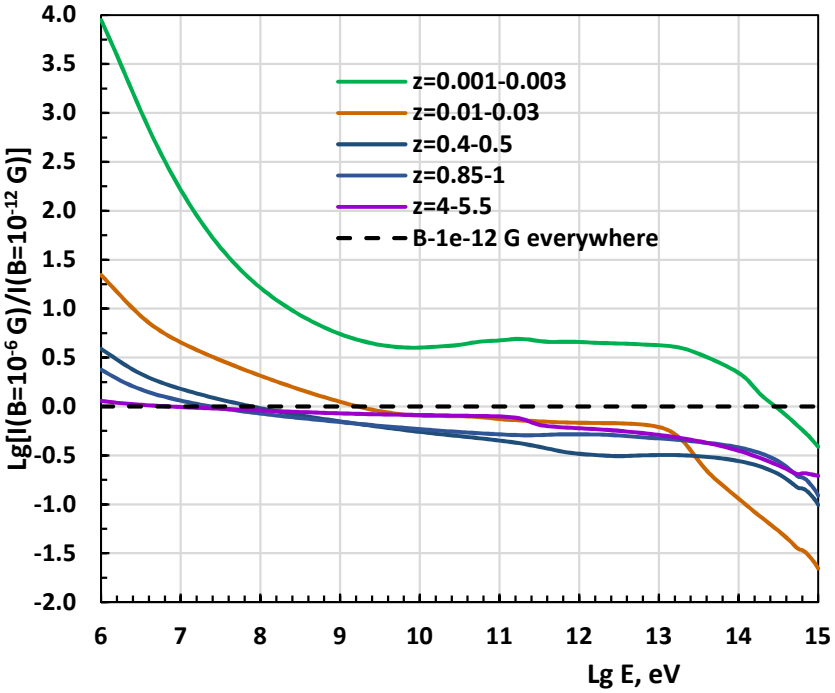


Figure 2. The ratio of cascade gamma-ray intensity with $B = 10^{-6}$ G to that with $B = 10^{-12}$ G for UHECR sources at various distances from Earth (see the legend).

As shown in Figure 2, the nearer the sources, the higher the energy at which log$R = 0$. The biggest difference is between the curves in two extreme cases: for nearby sources with red shifts $z \approx 0.0012$–0.003 and remote sources with $z = 4$–5.5. The reason for the difference between curves is the following:

UHECRs emitted from nearby sources give no rise to cascades, as free paths of electrons and quanta are longer than distances from the sources [28], so cascades do not develop. Electrons are born only via μ^+ and neutron decay, gamma-rays are produced only in π^0-decays and the synchrotron emission of electrons. π^0-decays produce few quanta [28], and the quanta main source is synchrotron emission. It depends on EGMF and as a result the intensity of gamma-ray emission (the most of which is synchrotron emission) is much higher in the EGMF of 10^{-6} G than that in the EGMF of 10^{-12} G, compared with the case of remote sources.

In addition, UHECRs from remote sources initiate cascades, in which electrons spend energy both in IC-scattering and synchrotron emission. Then, a smaller part of electron energy is spent on synchrotron radiation compared to nearby sources, thus, smaller parts of cascade gamma-rays are of synchrotron origin. So, the larger the distances from sources, the weaker the EGMF influence. Additionally, energy dissipation in cascade leads to a loss of information, in which processes cascade particles spend the energy [6], either in IC-scattering or synchrotron emission Thus, the farther the sources, the fweaker the difference between curves and the line corresponding to the case $B = 10^{-12}$ G. The smallest difference is between this line and the curve for sources at $z = 4$–5.5. In addition, in the case of remote sources, the synchrotron quanta energies being lower, the energy value at which log$R = 0$ shifts to smaller values. In the model, the bulk of sources is located at $z \leq 2.5$ [24], setting curve crossing in Figure 1.

In the range of ~10^7–10^9 eV, relative curve deviation from each other is minimal, being of 0.25–0.3. Closeness of curves is due to the cascade 'universality' described in [6]. At higher energies (to ~10^{19} eV), the deviation is of ~10.

In the range of ~10^7–10^9 eV, the intensity of cascade gamma-ray emission is least dependent on EGMF. Thus, at energies of ~10^7–10^9 eV, it is possible to study the contribution

of cascade emission to the extragalactic gamma-ray background without specific models of the extragalactic magnetic field.

4. Conclusions

EGMF influence diffuses cascade gamma-ray emission through synchrotron radiation of cascade electrons and IC scattering of synchrotron quanta. EGMF of ~10^{-12} G and lower evidently has no influence on electromagnetic cascades from UHECRs. The higher magnetic field exists inside galaxies and galactic clusters, where it is of ~10^{-6} G, and in sheets and filaments where it is of ~10^{-7}–10^{-9} G. All these structures fill the insignificant part of space and the EGMF effect on the cascade emission is minor. Yet the knowledge of this effect can be relevant in the search for DM particles. The reason is the following. Gamma-quanta arise in the decay of particles produced in DM particle annihilation. Thus, any excess in gamma-ray background intensity is analyzed when searching DM particles. In view of this, components of the extragalactic background emission should be known, one of which is cascade gamma-rays.

For that reason, we analyze the EGMF influence on the diffuse cascade gamma-ray spectra. We consider the model in which the extragalactic magnetic field is uniform, its strength being a model parameter, and compare cascade gamma-ray spectra in EGMF with $B = 10^{-6}$ and $B \leq 10^{-12}$ G. We obtain that the relative difference between the spectra is minimal, of 0.25–0.3, in the energy range of ~10^{7}–10^{9} eV. The relative space volume occupied by a field of ~10^{-6} G being small, this difference is minor, thus, in this energy range, specific models of extragalactic magnetic field are not required to study the contribution of diffuse cascade emissions in the extragalactic gamma-ray background.

The result obtained is seemingly valid also for purely electromagnetic cascades, as was discussed in [29].

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Acknowledgments: The author thanks O. Kalashev for the discussion of the code TransportCR and extragalactic cascade features, T. Dzhatdoev for the discussion of extragalactic magnetic fields. The author thanks referees for remarks and discussion of the text.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Greisen, K. End to the Cosmic-Ray Spectrum? *Phys. Rev. Lett.* **1966**, *16*, 748. [CrossRef]
2. Zatsepin, G.T.; Kuz'min, V.A. Upper Limit of the Spectrum of Cosmic Rays. *JETP Lett.* **1966**, *4*, 78.
3. Hayakawa, S. Electron-Photon Cascade Process in Intergalactic Space. *Prog. Theor. Phys.* **1966**, *37*, 594. [CrossRef]
4. Prilutsky, O.; Rozental, I.L. Cascade processes in the metagalaxy. *Acta Phys. Hung. Suppl.* **1970**, *129*, 51.
5. Berezinsky, V.S.; Bulanov, S.V.; Dogiel, V.A.; Ginzburg, V.L.; Ptuskin, V.S. *Astrophysics of Cosmic Rays*; Ginzburg, V.L., Ed.; North-Holland, Elsevier Science Publishers B.V.: Amsterdam, The Netherlands, 1990.
6. Berezinsky, V.; Kalashev, O. High-energyelectromagnetic cascades in extragalactic space: Physics and features. *Phys. Rev. D* **2016**, *24*, 023007. [CrossRef]
7. Uryson, A.V. Identification of extragalactic cosmic-ray sources using data from various detection facilities. *JETP* **1998**, *86*, 213. [CrossRef]
8. Dolag, K.; Grasso, D.; Springel, V.; Tkachev, I. Constrained simulations of the magnetic field in the local Universe and the propagation of ultrahigh energy cosmic rays. *JCAP* **2005**, *01*, 009. [CrossRef]
9. Elyiv, A.; Neronov, A.; Semikoz, D.V. Gamma-ray induced cascades and magnetic fields in the intergalactic medium. *Phys. Rev. D* **2009**, *80*, 023010. [CrossRef]
10. Abbasi, R.U.; Abe, M.; Abu-Zayyad, T.; Allen, M.; Azuma, R.; Barcikowski, E.; Belz, J.W.; Bergman, D.R.; Blake, S.A.; Cady, R.; et al. TA collaboration. Evidence for a Supergalactic Structure of Magnetic Deflection Multiplets of Ultra-high-energy Cosmic Rays. *Astrophys. J.* **2020**, *899*, 86. [CrossRef]
11. Dzhatdoev, T.A.; Podlesnyi, E.I.; Vaiman, I.A. Can we constrain the extragalactic magnetic field from very high energy observations of GRB 190114C? *Phys. Rev. D* **2020**, *102*, 123017. [CrossRef]

12. Govoni, F.E.; Orrù, E.; Bonafede, A.N.; Iacobelli, M.; Paladino, R.; Vazza, F.R.; Murgia, M.A.; Vacca, V.A.; Giovannini, G.; Feretti, L.; et al. A radio ridge connecting two galaxy clusters in a filament of the cosmic web. *Science* **2019**, *364*, 981. [CrossRef] [PubMed]
13. Roszkowski, L.; Sessolo, E.M.; Trojanowski, S. WIMP dark matter candidates and searches-current status and future prospects. *Rep. Prog. Phys.* **2018**, *81*, 066201. [CrossRef] [PubMed]
14. Fargion, D.; Mele, B.; Salis, A. Ultra-High-Energy Neutrino Scattering onto Relic Light Neutrinos in the Galactic Halo as a Possible Source of the Highest Energy Extragalactic Cosmic Rays. *ApJ* **1999**, *517*, 725. [CrossRef]
15. Fargion, D.; Colaiuda, A. Gamma rays precursors and afterglows surrounding UHECR events: Z-burst model is still alive. *Nucl. Phys. B. Proc. Suppl.* **2004**, *136*, 256. [CrossRef]
16. Fargion, D.; Oliva, P. Updated Z-Burst Neutrinos at Horizons. *Nucl. Phys. B (Proc. Suppl.)* **2007**, *165*, 116. [CrossRef]
17. Fargion, D.; D'Armiento, D.; Paggi, P. UHECR bending, clustering and decaying feeding gamma anisotropy. *IL Nuovo Cim.* **2013**, *36*, 139.
18. Kalashev, O.E.; Kido, E. Simulations of ultra-high-energy cosmic rays propagation. *JETP* **2015**, *120*, 790. [CrossRef]
19. Istomin Ya, N.; Gunya, A.A. Acceleration of high energy protons in AGN relativistic jets. *Phys. Rev. D* **2020**, *102*, 043010. [CrossRef]
20. Uryson, A.V. Identification of sources of ultrahigh energy cosmic rays. *Astron. Rep.* **2001**, *45*, 591. [CrossRef]
21. Krymskii, G.F. A regular mechanism for the acceleration of charged particles on the front of a shock wave. Soviet Physics—Doklady 22 327. *Akad. Nauk. SSSR Doklady.* **1977**, *234*, 1306.
22. Bell, A.R. The acceleration of cosmic rays in shock fronts – I. *MNRAS* **1978**, *182*, 147. [CrossRef]
23. Cesarsky, C.J. Cosmic rays with E > 10**19-eV: Origin and transport. *Nucl. Phys. B (Proc. Suppl.)* **1992**, *28*, 51. [CrossRef]
24. Giacinti, G.; Kachelrieß, M.; Kalashev, O.; Neronov, A.; Semikoz, D.V. Unified model for cosmic rays above 10^{17} eV and the diffuse gamma-ray and neutrino backgrounds. *Phys. Rev. D* **2015**, *92*, 083016. [CrossRef]
25. Protheroe, R.J.; Biermann, P.L. A new estimate of the extragalactic radio background and implications for ultra-high-energy γ-ray propagation. *Astropart Phys.* **1996**, *6*, 45, **1997**, *7*, 181(E).
26. Inoue, Y.; Inoue, S.; Kobayashi, M.A.; Makiya, R.; Niino, Y.; Totani, T. Extragalactic background light from hierarchical galaxy formation: Gamma-ray attenuation up to the epoch of cosmic reionization and the first stars. *Astrophys. J.* **2013**, *768*, 197. [CrossRef]
27. Ginzburg, V.L.; Syrovatskii, S.I. *The Origin of Cosmic Rays*; Massey, H.S.H., Ter Harr, D., Eds.; Pergamon Press: Oxford, UK; Macmillan: London, UK, 1964.
28. Uryson, A.V. The possibility of investigating ultra-high-energy cosmic-ray sources using data on the extragalactic diffuse gamma-ray emission. *Astron. Lett.* **2017**, *43*, 529. [CrossRef]
29. Dzhatdoev, T.; Khalikov, E.; Podlesnyi, E.; Telegina, A. Intergalactic γ-ray propagation: Basic ideas, processes, and constraints. *J. Phys. Conf. Ser.* **2019**, *1181*, 012049. [CrossRef]