Gamma rays from Galactic Pulsars

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Abstract

Gamma rays from young pulsars and milli-second pulsars are expected to contribute to the diffuse gamma-ray emission measured by the Fermi Large Area Telescope (LAT) at high latitudes. We derive the contribution of the pulsars undetected counterpart by using information from radio to gamma rays and we show that they explain only a small fraction of the isotropic diffuse gamma-ray background.

Keywords: gamma rays, Galaxy

1. The isotropic diffuse gamma-ray background

Since 5 years, the Fermi Large Area Telescope (LAT) surveys the gamma-ray sky in the GeV energy range. Besides discovering the emission of individual gamma-ray point-like sources such as blazars, star-forming galaxies and pulsars, the Fermi-LAT has confirmed and measured a faint and almost isotropic emission at high latitudes: the isotropic diffuse gamma-ray background (IGRB) \cite{1}. The relevance of the IGRB is twofold: on the one hand, it is believed to be the superposition of several astrophysical contributions, both unresolved sources and diffuse processes; on the other hand, it can be partly due to the gamma-ray emission from dark matter annihilation in the Galaxy and in external galaxies. For this reasons, studying the IGRB is of utmost importance to shed light onto the nature of extragalactic and Galactic astrophysical sources as well as to reduce the uncertainty for dark matter searches by means of this target \cite{2}. In Sec. 2 we summarize the properties of pulsars and MSP population, their spatial distribution in the Galaxy and their gamma-ray spectral properties as derived from the Second Fermi-LAT Catalog of gamma-ray pulsars (2FPC) \cite{5}. In Sec. 3 we describe the procedure we follow to generate a mock pulsar and MSP population and its gamma-ray emission. We then present our results about the emission from unresolved young pulsars and MSPs at high- and low-latitudes. Finally, we draw our conclusions in Sec. 4.

2. The pulsar population

Pulsars are spinning neutron stars with a rotation period of a few milli-seconds up to tens of seconds (separation at $P = 15$ ms). The magnetic dipole braking slows down the pulsar rotation period $\dot{P}$ and the subsequent energy loss rate, or spin-down luminosity, is $\dot{E} = 4\pi^2 VP^3/3$, where $P$ is the period derivative and $M$ is the moment of inertia of the star ($10^{45}$ g cm$^2$). The radiation from the star is obtained through the conversion of the spin-down luminosity with a given efficiency.
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3. The pulsar gamma-ray sky

We simulated the all-sky gamma-ray emission due to an MSP population modeled as described above. Each simulated object was identified by its period, magnetic field and position in the Galaxy, as randomly extracted from the corresponding distributions. Period and magnetic field determine the spin-down luminosity of the simulated source. By extracting \( \eta \) from a uniform distribution in the allowed band, the gamma-ray luminosity can be derived as well as the gamma-ray energetic flux \( S_\gamma = L_\gamma/(4\pi d^2) \). The energetic flux of each source is used to determine if such an object would be detected or not by the Fermi-LAT, by comparing the expected \( S_\gamma \) from that source with the detection sensitivity curve from the 2FPC (Fig. 17 of [5]). In this way, we got a collection of non-detected sources that contribute to the IGRB as diffuse emission, while the number of detected objects cannot be larger than the truly observed one. We assigned to each simulated source a value of \( \eta \) and \( E_{\text{cut}} \) extracted from the corresponding distributions. The spectral parameters allow to compute the gamma-ray flux that is, in turn, needed to find the spectrum of the source \( dN/dE \). The contribution to the IGRB from the unresolved source population, above a given latitude, is given by the sum of the \( dN/dE \) of all sources below the detection threshold. Figure 1 shows the resolved and unresolved counterpart of one Monte Carlo realization.

The emission from unresolved MSPs at latitudes above 10° is shown in Figure 2. The contribution to the IGRB from unresolved MSPs turns out to be about 0.1%–0.9% at the peak (2 GeV) and about 0.02%–0.13% of the integrated IGRB intensity. The uncertainty band is of \( O(10) \) at all energies.
Figure 2: Diffuse gamma-ray flux from the MSP unresolved population. The red solid line represents the average over 1000 Monte Carlo realizations, while the light orange band is the 1σ uncertainty band.

We also computed the emission in the inner part of the Galaxy where, recently, several and independent analyses have found an excess above the standard astrophysical background, the so-called “Fermi GeV excess” (as for example [10,11,12,13]. We considered two regions: $10^\circ \leq |\theta| \leq 20^\circ$ and $l \in [-180^\circ, 180^\circ],$ and $|\theta| \leq 3.5^\circ$ and $|l| \leq 3.5^\circ$ (the Galactic center region). Beside the MSP contribution, we include the emission of young pulsars (by applying to this population the same methodology outlined above), since pulsars are known to be concentrated more along the disk and might produce a significant emission. In both regions, the contribution from unresolved young pulsars and MSPs might explain only up to 5%–10% of the GeV excess. While the spectral properties of young pulsars and MSPs are compatible with the excess, the flux they can produce is not enough to fully explain the signal (see also [14,15]). Nevertheless, it might possible that a population component associated with the Galactic bulge could explain the intensity and morphology of the excess [16].

4. Conclusion

We performed a systematic analysis of pulsar and MSP population properties from radio (ATNF catalog) to gamma rays (Fermi-LAT). We demonstrated that MSPs are a marginal component of the IGRB with an uncertainty of O(10) at all energies. MSPs are also a negligible contributor to the gamma-ray anisotropy signal measured by the Fermi-LAT, thus indicating that this should be dominated by other sources. At low latitudes, the contribution from both young pulsars and MSPs can explain up to about 10% of the excess emission measured in the inner part of the Galaxy. The MSPs interpretation of the Fermi-LAT GeV excess is thus in tension with spectral and morphological properties of the MSP disk-like population as we model it from radio and gamma-ray observations.

References

[1] A. A. Abdo, M. Ackermann, M. Ajello, et al., Spectrum of the Isotropic Diffuse Gamma-Ray Emission Derived from First-Year Fermi Large Area Telescope Data, Physical Review Letters 104 (10) (2010) 101101. [arXiv:1002.3603 doi:10.1103/PhysRevLett.104.101101]
[2] T. Bringmann, F. Calore, M. Di Mauro, F. Donato, Constraining dark matter annihilation with the isotropic γ-ray background: updated limits and future potential, Phys.Rev. D89 (2014) 023012. [arXiv:1303.3284 doi:10.1103/PhysRevD.89.023012]
[3] M. Ackermann, et al., Anisotropies in the diffuse gamma-ray background measured by the Fermi LAT, Phys.Rev. D85 (2012) 083007. [arXiv:1202.2856 doi:10.1103/PhysRevD.85.083007]
[4] C.-A. Faucher-Giguère, A. Loeb, The pulsar contribution to the gamma-ray background, jcap 1 (2010) 5. [arXiv:0904.3102 doi:10.1088/1475-7516/2010/01/005]
[5] A. A. Abdo, M. Ajello, A. Allafort, et al., The Second Fermi Large Area Telescope Catalog of Gamma-Ray Pulses, apjs 208 (2013) 17. [arXiv:1305.4336 doi:10.1088/0067-0049/208/2/17]
[6] A. G. Lyne, The magnetic fields of neutron stars, in: Astronomy, physics and chemistry of H’3, Vol. 358 of Royal Society Philosophical Transactions Series A, 2000, pp. 831–840. [doi:10.1098/rsta.2000.0561]
[7] F. Calore, M. Di Mauro, F. Donato, Diffuse gamma-ray emission from galactic pulsars, Astrophys.J. 796 (2014) 1. [arXiv:1406.2706 doi:10.1088/0004-637X/796/1/14]
[8] R. N. Manchester, G. B. Hobbs, A. Teoh, M. Hobbs, The Australia Telescope National Facility Pulsar Catalogue, AJ129 (2005) 1993–2006. [arXiv:astro-ph/0412641 doi:10.1086/428488]
[9] M. Ackermann, Intensity and origin of the extragalactic gamma-ray background, 4th Fermi Symposium, http://galprop.stanford.edu/resources.php.
[10] O. Macias, C. Gordon, The Contribution of Cosmic Rays Interacting With Molecular Clouds to the Galactic Center Gamma-Ray Excess, Phys.Rev. D89 (2014) 063515. [arXiv:1312.6671 doi:10.1103/PhysRevD.89.063515]
[11] K. N. Abazajian, N. Canac, S. Horiiuchi, M. Kaplinghat, Astrophysical and Dark Matter Interpretations of Extended Gamma Ray Emission from the Galactic Center [arXiv:1402.4090]
[12] T. Daylan, D. P. Funkheimer, D. Hooper, et al., The Characterization of the Gamma-Ray Signal from the Central Milky Way: A Compelling Case for Annihilating Dark Matter [arXiv:1502.06703]
[13] F. Calore, I. Cholis, C. Weniger, Background model systematics for the Fermi GeV excess [arXiv:1409.0042]
[14] D. Hooper, I. Cholis, T. Linden, J. Siegel-Gaskins, T. Slatyer, Millisecond pulsars Cannot Account for the Inner Galaxy’s GeV Excess, Phys.Rev. D88 (2013) 083009. [arXiv:1305.0830 doi:10.1103/PhysRevD.88.083009]
[15] I. Cholis, D. Hooper, T. Linden, Challenges in Explaining the Galactic Center Gamma-Ray Excess with Millisecond Pulsars [arXiv:1407.5825]
[16] J. Petrovic, P. D. Serpico, G. Zaharijas, Millisecond pulsars and the Galactic Center gamma-ray excess: the importance of luminosity function and secondary emission [arXiv:1411.2980]