The *Fermi* LAT view of Cygnus: a laboratory to understand cosmic-ray acceleration and transport

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Abstract

Cygnus X is a conspicuous massive-star forming region in the Local Arm of the Galaxy at $\sim 1.4$ kpc from the solar system. $\gamma$-ray observations can be used to trace cosmic rays (CRs) interacting with the ambient interstellar gas and low-energy radiation fields. Using the Fermi Large Area Telescope (LAT) we have discovered the presence of a 50-pc wide cocoon of freshly-accelerated CRs in the region bounded by the ionization fronts from the young stellar clusters. On the other hand, the LAT data show that the CR population averaged over the whole Cygnus complex on a scale of $\sim 400$ pc is similar to that found in the interstellar space near the Sun. These results confirm the long-standing hypothesis that massive star-forming regions host CR factories and shed a new light on the early phases of CR life in such a turbulent environment.

Keywords: cosmic rays, gamma rays, acceleration of particles, open clusters and associations

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1. Introduction

Cosmic rays (CRs) are one of the most intriguing puzzles of the last century Physics. It is strongly advocated that Galactic CRs are accelerated by supernova remnants (SNRs), which are energetic and numerous enough to sustain the CR population directly measured near the Earth \[1\]. A plausible mechanism for CR acceleration in SNRs is provided by non-linear diffusive shock acceleration. The presence of high-energy electrons in SNRs is undoubtedly demonstrated by their multiwavelength spectrum. On the other hand, the acceleration of nuclei is an elusive phenomenon, which, from the observational point of view, so far is supported mainly by the impact of efficient ion acceleration on the thermohydrodynamics of the shockwaves, as inferred from X-ray observations, and from the spectral shape of $\gamma$-ray emission [e.g. \[2\].

The isotopic abundances measured for CRs indicate that $\sim 20\%$ of the material is synthesized by Wolf-Rayet (WR) stars 100 kyr before the acceleration \[3\]. WR stars represent an evolutionary stage of massive OB stars, and the latter cluster in space and time within the so-called OB associations. Additionally, $\sim 80\%$ of SNRs originate from the gravitational collapse of a massive-star core, therefore often inside an OB association. All these considerations have given credence to the hypothesis that at least part of the CRs are accelerated by the repeated action of shockwaves from massive stellar winds and SNRs inside massive stellar clusters.

The propagation of high-energy CRs in the interstellar space is often described in terms of diffusion by magnetohydrodynamic turbulence with the possible inclusion of convection and reacceleration \[4\]. While propagating, CRs lose their energy through many different interaction processes. Electromagnetic radiation arising from such interactions is the only probe we have
of CR properties in the Galaxy beyond direct measurements performed in the solar system. Interstellar γ-ray emission is produced by CR interactions with the interstellar medium, via nucleon-nucleon inelastic collisions and electron Bremsstrahlung, and with the low-energy interstellar radiation fields via inverse-Compton (IC) scattering by electrons.

The intermediate steps, i.e. the escape of CRs from their sources and the early propagation in the surrounding medium, have escaped observations so far. Massive stars generate intense radiation, powerful winds and explosions which alter their neighborhood and power fast shockwaves and strong supersonic turbulence. If part of the CRs are accelerated in regions of massive-star shockwaves and strong supersonic turbulence. If part of the CRs are accelerated in regions of massive-star formation, this turbulent medium influences their evolution, e.g. through confinement and reacceleration phenomena counter-balanced by increased radiative losses.

The Cygnus X region is home to numerous massive stellar clusters embedded in a complex of giant molecular clouds. Most of the molecular gas along the line of sight shows interactions with the stellar clusters, notably with Cyg OB2 at a distance of ∼1.4 kpc [6]. At a comparable distance we find the SNR γ Cygni, e.g. [7], which appears as a potential CR accelerator. In addition, Milagro detected very high-energy γ-ray emission from the complex [8], pointing to the presence of enhanced CR densities.

In this paper we summarize the results of our analysis of two years of high-energy γ-ray observations of the Cygnus complex by the Fermi Large Area Telescope (LAT) [9]. The results, discussed in detail in [10][11], reveal an unexpected scenario, where the low-density cavities blown by the massive stellar clusters form a cocoon for freshly-accelerated particles, whereas the CR population averaged over the whole complex is similar to that found in other more quiet segments of the Local Arm.

2. Data and Analysis

We analyzed the region at Galactic longitudes 72° ≤ l ≤ 88° and latitudes −15°b + 15°. The multiwavelength data and analysis method are detailed in [11]; in this section we summarize the main features. We have used γ-ray data from the first two years of observations by the Fermi LAT between 100 MeV and 100 GeV, applying tight rejection criteria to reduce the backgrounds due to charged CRs and the Earth’s atmospheric emission. Below 1 GeV we accepted only γ-rays that converted into pairs in the thin section of the LAT tracker, to reduce the angular resolution degradation due to multiple Coulomb scattering.

The model described hereafter was fitted to the LAT data by a binned maximum likelihood procedure on a 0.125° × 0.125° angular grid and independently for 10 energy bins spanning the whole energy range considered, using post-launch LAT instrument response functions.

Since the densities of the bulk of Galactic CRs are expected to vary only on scales larger than those of the gas clouds, we modeled interstellar γ-ray emission from their interactions as a linear combination of components traced by atomic hydrogen (H I) and CO (as a surrogate of molecular hydrogen, H 2) split along the line of sight to separate the Cygnus complex from the more distant Perseus and outer spiral arms, plus visual extinction residuals to take into account the neutral interstellar gas missed by these two tracers. We added an IC model calculated using the GALPROP code [4] and an isotropic component to account for the extragalactic diffuse γ-ray background and the residual background due to charged CR interactions in the LAT.

Below a few GeV the γ-ray emission from the region is dominated by the three bright pulsars J2021 + 3651, J2021 + 4026 and J2032 + 4127. To be more sensitive to interstellar structures, at energies <10 GeV their emission was dimmed by excluding from the analysis photons detected in their periodic pulses in a circular region around each pulsar with a radius comparable to the LAT point-spread function (PSF) 95% containment as a function of energy.

Other sources from the 1FGL Catalog [12] either identified with, or associated with high-confidence to sources known from other wavelengths were included as well in the analysis model. We modeled γ-ray extended emission associated to the Cygnus Loop SNR as described in [13].

We detected significant γ-ray emission associated with the radio shell of the γ Cygni SNR and the very high-energy γ-ray source VER J2019+407 located on its rim. They were modeled using geometrical templates, namely a 0.5° disk for the radio shell of the SNR [14] and a Gaussian for VER J2019+407 [15].

Residuals remain unaccounted for after fitting this model, hereafter the background model, to the LAT data (Fig. [7]). The residuals peak toward the central star-forming region of Cygnus X. We modeled the excess as a Gaussian, obtaining as best-fit parameters (l, b) = (79.6° ± 0.3°, 1.4° ± 0.4°) for the centroid and a radius of 2.0° ± 0.2°, with an improvement in the fit to the data above 1 GeV at the ~10σ level. The hypothesis of extended emission provides a better fit to the data than an ensemble of discrete point sources. No spectral variations across the emission region could be detected [10].
The residual emission (Fig. 1) extends from the Cyg OB2 stellar cluster to the γ Cygni SNR, peaking toward the most conspicuous clusters like Cyg OB2 itself and NGC 6910. However, it is more broadly distributed than any of these objects. It is unlikely that the broad γ-ray excess is produced by a wind nebula powered by PSR J2021+4026 (likely to be associated with the 7-kyr old γ Cygni SNR) or by PSR J2032+4127 (which is probably located behind Cygnus in the Perseus arm, [16]). We cannot rule out the presence of a wind nebula powered by a yet undiscovered pulsar, but the morphology of the γ-ray excess strongly suggests an interstellar origin. Indeed, the γ-ray excess is bounded by the photon-dominated regions, visible through dust emission at 8 μm. The excess closely follows the morphology of the ionized cavities formed by the boisterous winds of the numerous massive star clusters in Cygnus X, as in a cocoon.

### 3. A Cocoon of Freshly Accelerated Cosmic Rays in Cygnus X

The emission from the cocoon is hard and extends to 100 GeV. The cocoon overlaps the TeV source MGRO J2031+41 detected by Milagro. Those overlap as well the arcmin source TeV J2032+4130 detected by HEGRA and MAGIC. However, the flux measured by Milagro above 10 TeV exceeds the extrapolation of that measured by HEGRA at lower energies [8].

Ionized gas was not part of the background model. It can be traced by free-free emission in the microwave band. Adding an ionized gas template instead of the 2° Gaussian provides an equally good fit, but only at the expense of a hard spectrum, much harder than for the other gas phases (§4). It is consistent with that obtained with the Gaussian template [10, Fig. S7].

In Fig. 2 we compare the γ-ray spectrum of the cocoon with predictions based on the local CR spectrum, i.e., the CR spectrum in the interstellar space near the...
Earth inferred from direct CR measurements, γ-ray observations of nearby clouds and radio observations of synchrotron emission produced by CR electrons and positrons. Such predictions fail to reproduce the observed γ-ray spectrum. If we assume that the emission is purely hadronic we need to amplify the γ-ray positrons. Such predictions fail to reproduce the optical and infrared radiation fields pervading the Cygnus X cavities, as well as from the enhanced optical and infrared radiation fields pervading the Cygnus X cavities, including emission from the AGN 6910 (lower –black– dotted line), as well as from the enhanced optical and infrared radiation fields pervading the Cygnus X cavities (lower dashed line). From [10].

Figure 2: Spectral energy distribution of the cocoon (filled circles). Below 1 GeV 95% confidence upper limits. The empty circle gives the flux of MGRO J2031−41 subtracted by the flux of the compact source TeV 2032+4130 extrapolated at energies > 10 TeV [3]. The continuous (blue) line and upper dashed (blue) line show the spectrum expected from ionized gas illuminated by CRs with the local interstellar spectrum, assuming an effective electron density of $n_{\text{eff}} \approx 10 \, \text{cm}^{-3}$ and 2 cm$^{-3}$, respectively, to calculate the ionized gas densities from free-free emission intensities. The intermediate (red) dashed line shows the total IC expected if CRs had the local interstellar spectrum across the Cygnus X region, including emission from the x-ray emitting Cyg OB2 (upper –black– dotted line) and NGC 6910 (lower –black– dotted line), as well as from the enhanced optical and infrared radiation fields pervading the Cygnus X cavities (lower dashed line). From [10].

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Figure 3: $\gamma$-ray emissivity per hydrogen atom averaged over the whole interstellar cloud complex of Cygnus. Points include statistical uncertainties only, whereas the dashed bands show the systematic uncertainties related to the H_I column densities and to the LAT effective area. The dashed (blue) curve shows the model for the local interstellar spectrum consistent with LAT observations of nearby interstellar clouds [19]. From [11].

Figure 4: $\gamma$-ray emissivity of atomic hydrogen at energies $> 200$ MeV measured by the LAT in the Cygnus region (red or light gray), the second Galactic quadrant [21] (black) and the third Galactic quadrant [22] (blue or gray). Results are shown for different values of the H_I spin temperature $T_S$, i.e. the parameter used to determine from radio observations the column densities of atomic hydrogen, which are currently the main source of uncertainty in this kind of measurement.

5. Summary

The Fermi LAT observations of Cygnus have added a few more pieces to the puzzle of Galactic CRs. The discovery of a cocoon of freshly-accelerated CRs in Cygnus X confirms the long-standing hypothesis that massive-star forming regions house particle accelerators. It provides an observational test case to study the escape of CRs from their sources and the impact of wind-powered turbulence on their early evolution. It also sheds a new light on the observation of TeV $\gamma$-ray emission from regions harboring massive stellar clusters [e.g. 25, 26, 27].

The similarity of the CR population averaged over the whole Cygnus complex to that in the rest of the Local Arm and in the outer Galaxy strengthens the discrepancy found between LAT observations and propagation models that predict a strong coupling over a scale of $\sim 1 - 2$ kpc between CR source densities and CR fluxes. Studies of Fermi $\gamma$-ray observations of massive star-forming complexes in the inner Galaxy are required to further investigate this issue.

Some of the usual assumptions concerning the injection and transport of CRs in the interstellar space are challenged by the current observations. Better understanding the propagation and interactions of CRs has important implications for the physics of the interstellar medium, hence for star formation, in the Milky Way,
as well as in other galaxies including starbursts. It is also a crucial prerequisite to look for any tracks of still unknown physical processes hidden in the sea of energetic particles filling the Universe, such as the products of decay or annihilation of dark-matter particles. All in all, the next century of CR Physics looks as exciting as the past one.

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