



## The *Fermi* Large Area Telescope unveils a cocoon of freshly-accelerated cosmic rays in the Cygnus X region

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**Abstract:** Supernova remnants are generally considered as the accelerators of the Galactic cosmic rays. The majority of supernovae have massive star progenitors and explode in a highly turbulent medium sustained by stellar winds and intense ionizing radiation in and around the parent stellar clusters. The early diffusion of cosmic rays after their injection in the turbulent medium and the potential confinement and reacceleration of the particles in this environment have escaped observations so far. Their propagation through gas and soft radiation fields can be traced in gamma rays. We will present an analysis of the *Fermi* Large Area Telescope (LAT) observations of the Cygnus X region: gamma-ray emission above 1 GeV reveals a cocoon of freshly-accelerated cosmic rays following the cavities carved by Cyg OB2 and other young stellar clusters. We will discuss the cocoon properties and the origin of the particles from the nearby  $\gamma$ -ray bright supernova remnant  $\gamma$  Cygni or the Cygnus superbubble.

**Keywords:** cosmic rays: acceleration – cosmic rays: propagation – gamma rays: diffuse emission – massive stars – superbubble – supernova remnant

### 1 The puzzle of Galactic cosmic rays

After about one century from their discovery, cosmic rays (CRs) are still a puzzle to physicists and astrophysicists. The CR spectrum extends over many decades in energy with a first remarkable feature around  $3 \times 10^{15}$  eV, the *knee*, which is thought to mark the transition between the part dominated by Galactic and extragalactic sources. The strongest indication that below the *knee* CRs are originate in the Galaxy is indirectly given by the high energy  $\gamma$ -ray emission they produce when they diffuse through interstellar matter and soft radiation fields, which appears different from galaxy to galaxy, e.g. [2].

It is strongly advocated that Galactic CRs are accelerated by supernova remnants (SNRs), which are the only astrophysical objects, except for  $\gamma$ -ray bursts, energetic and numerous enough to sustain the CR population directly measured near the Earth [13]. A plausible mechanism for CR acceleration in SNRs is provided by non-linear diffusive shock acceleration, consistently with most of the available observations, e.g. [7]. The presence of high-energy electrons in SNRs is undoubtedly demonstrated by their multi-wavelength 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, e.g. [12].

The isotopic abundances measured for CRs indicate that  $\sim 20\%$  of the material is synthesized by Wolf-Rayet (WR) stars 10 kyr before the acceleration [6]. WR stars represent an evolutionary stage of massive OB stars, and the latter cluster in space and time forming the so-called OB associations. Additionally,  $\sim 80\%$  of SNRs originate from the gravitational collapse of a massive-star core [10], and therefore often inside an OB association. All these considerations have been giving 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, e.g. [20]. In this *superbubble* scenario particles are naturally accelerated at energies above the *knee* [9], consistently with the smooth transition observed in the CR spectrum.

After leaving their sources, CRs spread in the interstellar space. They are not just a side-product of the energetic phenomena described above, but instead a fundamental component of the Galactic ecosystem [14]. They ionize and heat the interstellar medium (ISM), they contribute to hold the densest clouds in equilibrium against gravitational forces, they alter the interstellar magnetohydrodynamic turbulence and are possibly involved in the generation of the large-scale magnetic fields.

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 [22]. 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 near the Earth. Synchrotron emission seen in the radio domain is produced by CR electrons tangled by interstellar magnetic fields. Interstellar  $\gamma$ -ray emission is produced in interactions with the ISM, nucleon-nucleon inelastic collisions and electron Bremsstrahlung, and with the low-energy interstellar radiation via inverse-Compton scattering by CR 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, characterized by fast 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 against increased radiative losses.

Interestingly, very high-energy  $\gamma$ -ray emission suggested the presence of freshly-accelerated particles in regions of massive-star formation: Cygnus [1], the massive stellar cluster Westerlund 2 and its surrounding ionized cavity [4], the clouds in the Galactic ridge [3] which host the super-massive stellar clusters of the Arches, the Quintuplet and Sgr B2.

## 2 Looking for freshly-accelerated cosmic rays: Cygnus X

The Cygnus X region [11] hosts numerous massive stellar clusters [16] embedded in a complex of giant molecular clouds. It was long debated whether it is a coherent region or rather the superposition of distinct structures piling up along the line of sight in the direction tangent to the Local Arm. Recent high-resolution observations [21] indicate that most of the molecular gas along the line of sight shows interactions with the massive stellar clusters, notably with Cyg OB2 at a distance of  $\sim 1.4$  kpc [19].

At a comparable distance we find the SNR  $\gamma$  Cygni, e.g. [15], with an approximate age of 7 kyr and currently in the adiabatic expansion phase [17, 18], which appears as a potential CR accelerator. Together with the detection of very high-energy  $\gamma$ -ray emission by Milagro [1], this makes Cygnus X a promising target to look for freshly-accelerated CRs and possibly investigate their interplay with the turbulent medium surrounding massive stars.

We pursued this goal by analyzing high-energy  $\gamma$ -ray observations of Cygnus X by the *Fermi* Large Area Telescope (LAT) [5] between 100 MeV and 100 GeV. We sought a global model for the region including interstellar emission, point-like and extended sources [23]. The main challenge in this analysis consisted in disentangling all the different

components of the  $\gamma$ -ray emission measured by the LAT toward this crowded line of sight.

In this contribution we will present the detection of hard extended emission above 1 GeV toward the central part of Cygnus X. It follows the cavities carved in the ISM by the winds and ionization fronts from Cyg OB2, NGC 6910 and other massive stellar clusters, thus strongly suggesting an interstellar origin. Its hard spectrum is interpreted as the signature of freshly accelerated particles. The spectral properties of the  $\gamma$ -ray emission measured by the LAT will be discussed in the light of multiwavelength observations of Cygnus X, including those by TeV  $\gamma$ -ray telescopes. They will be used to investigate the origin of the particles in a single accelerator, like the  $\gamma$  Cygni SNR, or across the superbubble.

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