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What can Fermi LAT observation of the Galactic Centre tell us about its active past?

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Abstract. The Fermi-LAT gamma-ray data in the inner Galaxy region show several prominent features possibly related to the past activity of the Milky Way's super massive black hole. At a large, 50 deg scale, the Fermi LAT revealed symmetric hour glass structures with hard energy spectra extending up to 100 GeV (and dubbed 'the Fermi bubbles'). More recently and closer to the Galactic centre, at the 10 deg scale, several groups have claimed evidence for excess gamma-ray emission that appears symmetric around the Galactic center and has an energy spectrum peaking at few GeVs. We explore here the possibility that this emission originates in inverse Compton emission from high-energy electrons produced in a short duration, burst-like event injecting $10^{52} - 10^{53}$ erg, roughly 10^6 yrs ago. Several lines of evidence suggest that a series of 'burst like' events happened in the vicinity of our black hole in the past and gamma-ray observations may offer a new view of that scenario.

Keywords. Gamma rays, Galactic centre

1. Introduction

The center of our Galaxy represents one of the most interesting targets for astroparticle physics, as the observations of the non-thermal processes in the region offer the 'front seat view' on dense environments surrounding supermassive black holes and active star forming regions. In addition, the Galactic Centre (GC) is expected to be the brightest spot in terms of dark matter (DM) annihilation emission and is therefore an attractive target which could help resolve the long standing mystery of the nature of these particles which make up 85% of the matter density in the Universe (Ade *et al.* (2015)).

In this work we focus on gamma rays, which are copiously produced in interactions of cosmic rays with the interstellar medium and fields. They are also expected to be emitted in the self-annihilation or decay of dark matter particles in one of the most popular Weakly Interacting Massive Particle (WIMP) DM models.

The Fermi LAT satellite was launched in June 2008. It detects gamma rays in energy range 30 MeV to $\gtrsim$300 GeV†. Its data are public and actively used by the community‡. The diffuse gamma-ray emission from the cosmic ray population of the Milky Way constitutes majority of photons received by the LAT. In the crowded region of the Galactic center this emission is specially hard to model and to distinguish from the numerous non-thermal astrophysical sources, in part due to the limited angular resolution of the LAT. This challenges make this one of the hardest-to-model regions.

† $https://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm$
‡ $http://fermi.gsfc.nasa.gov/ssc/data/access/lat/$

Over the course of Fermi's eight year mission many groups have performed an analysis of the GC region, using the public Fermi LAT data (see e.g. Hooper *et al.* (2010), Calore *et al.* (2014), Ajello *et al.* (2015)). Most of the studies reached similar conclusion, that the commonly used ('pre Fermi') models of diffuse emission are not sufficient to explain the observation and that residual emission, dubbed the *'Galactic Centre Excess' (GCE)*, is present in this region at GeV energies.

The most important properties of the claimed residuals are i) the emission is extended, reaching up to few kilo-parsecs away from the GC with a $\sim r^{-2.4}$ profile (where r s the distance from the GC), ii) spectrum of the GCE can be modelled by a power law with an exponential cut-off (PLexp), of the type $E^{-\Gamma}\ \exp\left[-E/E_{\rm cut}\right]$ with parameters in the range $\Gamma = 0.5 \div 1$, $E_{\rm cut} \sim 2 \div 3$ GeV† and iii) Their total flux at 1-3 GeV, integrated within 1° of Galactic Center, is $\sim 10^{-10}$ erg cm^{-2} s^{-1}.

The claim that the GCE properties are exactly those expected from the annihilation of WIMP DM sparked significant attention. Among conventional astrophysical sources, cumulative emission from a population of unresolved milli-second pulsars (MSP) represent one of the most concrete possibilities (see e.g. Abazajian *et al.* (2012)). During the Fermi-LAT mission, numbers of detected gamma ray MSP discovered sky rocketed. Their spectra is intriguingly similar to the one inferred for the residuals, being a PLexp with $\Gamma \sim 1.5$, $E_{\rm cut} \sim 3.3$ GeV and they could naturally be produced during one of the past star burst periods in the region or possibly deposited there by the in-falling globular clusters in the past (Brandt *et al.* (2015)).

All the above mentioned contributions are by hypothesis *steady state*. We relax that assumption in Petrović *et al.* (2014) notting that the high energy sky is however significantly time-dependent, and some nuclear regions in external galaxies do show major signs of activity. We explore the possibility that the GCE might be an 'echo' of a past transient event at the GC, which injected high energy electrons in the medium. The GCE emission we observe today could then be due to the inverse Compton emission produced in the propagation of those electrons emitted in the past. Properties of the excess, in particular its i) energy cut-off, ii) spatial extension and iii) overall flux would then determine the age and total energy injected by the transient event. Similar idea was studied in Carlson *et al.* (2014), but in that case interactions of cosmic ray protons with the gas in the disk were considered as the source of the observed gamma rays.

2. Transient event in the Galactic Centre past?

The time-dependent spectrum $Q(E)$ of cosmic ray electrons injected in a bursting episode (a delta function in time and position), propagating (via diffusion and energy-losses) in a homogenous medium is well-known from classical literature on cosmic ray astrophysics. Here we closely follow Atoian *et al.* (1995), which provides a transparent and general analytical solution, allowing us to illustrate the main physical effects.

The energy distribution function of particles at time t post-burst and distance r from the source is given by

$$\frac{dn}{dE_e}(r,t,\gamma) = \frac{N_0\ \gamma^{-\alpha}}{\pi^{3/2}\ r_{\rm diff}^3}\left(1 - b\,t\,\gamma\right)^{\alpha-2}\ e^{-(r/r_{\rm diff})^2} \tag{2.1}$$

where $\gamma = E_e/m_e c^2$ parametrizes the energy E of electrons, α is the index of the electron injection spectrum, b accounts for inverse Compton and synchrotron energy losses as $d\gamma/dt = b\gamma^2$. As we are interested in a GC region extending up to 10 degrees we choose

† More recent data analyses which used larger data sets also detect emission above 10 GeV.

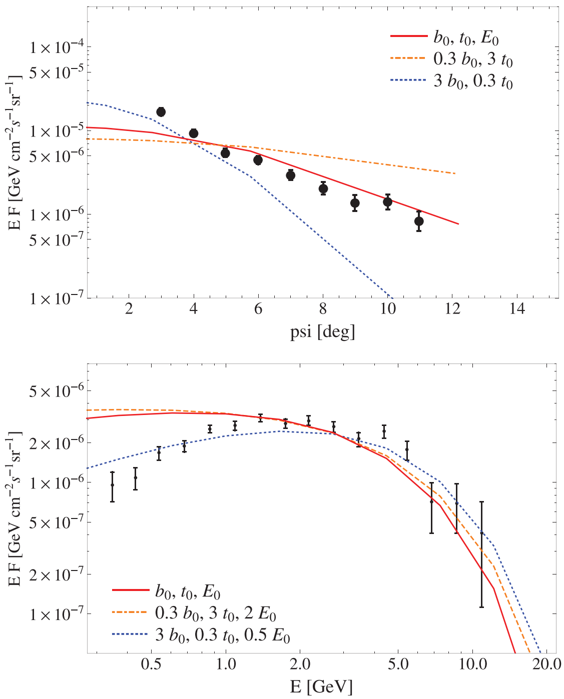

Figure 1. *Top Panel:* Latitude profile of the IC emission from an electron population injected t_0 (Red, Solid), 0.3 t_0 (Orange, Dashed) and 3 t_0 (Blue, Dotted) years ago (where $t_0 = 1$ Myr). *Bottom Panel:* The spectra of the IC emission (the same color scheme) at 5° away from the Galactic plane. The overall energetics is given in units of $E_0 = 4 \times 10^{52}$ erg.

values for the energy loss parameter which are higher than the locally measured ones, but appropriate for the Inner Galaxy.

Energy losses determine the *energy cut-off* in the electron spectrum set by the cooling in time t of electrons with formally infinite injection energy as $\gamma_{\rm cut} = (b\ t)^{-1}$.

The *spatial extension* of the electron flux is determined by the diffusion length $r_{\rm diff}$,

$$r_{\rm diff} = 2\left(D(\gamma)\ t\ \frac{1-(1-\gamma/\gamma_{\rm cut})^{1-\delta}}{(1-\delta)\gamma/\gamma_{\rm cut}}\right)^{1/2} \tag{2.2}$$

where the diffusion coefficient D is taken to be $D(\gamma) \simeq D_0\ (\gamma/\gamma_*)^{\delta}$, with $E_* = 3$ GeV, $\delta = 0.6$ and $D(10\ \text{GeV}) = 6\ 10^{28}\ \text{cm}^2/\text{s}$. As $r_{\rm diff}$ explicitly depends on the age of the source t, it breaks a degeneracy between the energy loss parameter b and age, which determine the spectral cut-off. The function $r_{\rm diff}$ also changes the spectrum in the sense of depleting the low-energy part of dn/dE_e the farther one is from the origin, at a given time, since less energetic electrons diffuse more slowly.

In order to calculate the Inverse Compton (IC) gamma-ray fluxes from this electron population we follow Colafrancesco *et al.* (2005). The IC emissivity can be written as

$$J_{IC}(E_\gamma) = \int dE_e\ \frac{dn_e}{dE_e}(E_e)\ P_{IC}(E_\gamma, E_e) \tag{2.3}$$

where dn_e/dE_e is given by Eq. (2.1) and P_{IC} is the inverse Compton power which depends on the energy and density of the Inter Stellar Radiation Field (ISRF) and the differential Klein-Nishina cross section.

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If we keep the spectral injection and diffusion indices fixed to their fiducial values, in principle one has **three observables:** spectral shape, angular shape and normalization with **four major parameters:** E_{TOT} (the total energy output of the source), D_0, b_0, t_0. The *angular shape* is controlled by $r_{\rm diff}$, which in turn can be altered via $(D_0\ t_0)$, see Eq.(2.2). This singles out a *Myr timescale* for t_0, for fiducial value of D_0. Once this parameter is fixed, only minor spectral slope adjustments are possible by varying $\alpha \in 2.1-2.4$, and $D_0(4\ \mathrm{GV}) = 2\ 10^{28} - 10^{29}\mathrm{cm}^2\mathrm{s}^{-1}$, but the key spectral parameter, the cutoff energy $E_{\rm cut} = m_e(b\,t_0)^{-1}$ is determined by the same parameter, t_0. It is remarkable that the observed cutoff in the spectrum is fully consistent with this estimate, as shown in Fig. 1. These analytic results have later been confirmed and studied in detail by a dedicated numerical simulation (Cholis *et al.* (2015)), which found that data are best described by a series of (two to three) leptonic bursts.

3. Summary

We show that a bursting event, injecting $\sim 10^{\mathbf{52}}$ ergs of energy in a standard power-law cosmic ray electron spectrum some Myrs ago can reproduce naturally the spectra and angular features of the claimed GeV excess in the inner Galaxy. Intriguingly, there are many hints that the GC may have experienced an active past, with the most spectacular manifestation provided by the “Fermi-LAT bubbles” (Su *et al.* (2010), Ackermann *et al.* (2014)). The main goal of our calculations was to raise awareness on the importance of accounting for transient events when dealing with extended excesses at the GC.

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