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# Acceleration of particles up to PeV energies at the galactic centre

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**Abstract.** Recent very high energy observations of the galactic centre region performed by H.E.S.S. revealed the presence of a powerful PeVatron. This is the first of such objects detected, and its most plausible counterpart seems to be associated to Sgr A*, the supermassive black hole in the centre of our galaxy. The implications of this discovery will be discussed, in particular in the context of the problem of the origin of galactic cosmic rays.

**Keywords.** Gamma rays: observations, Gamma rays: theory, Acceleration of particles

## 1. Introduction

The observed spectrum of Cosmic Ray (CR) protons extends up to the PeV energy domain, and then it steepens originating a feature called knee (Antoni *et al.* 2015, Bartoli *et al.* 2015). CRs of energy below that of the knee are believed to have a galactic origin, and this implies that our Galaxy must contain CR PeVatrons. The acceleration of PeV particles can be revealed indirectly by means of observations in the very high energy gamma-ray domain: protons of energy 1 $E_{\rm PeV}$ PeV interact with the ambient gas and produce neutral pions that in turn decay into gamma rays of typical energy $\sim 100$ $E_{\rm PeV}$ TeV (Aharonian 2004). Remarkably, the detection of a gamma-ray spectrum extending without significant attenuation up to the multi-TeV domain would constitute a proof of proton acceleration up to PeV energies, because competing leptonic mechanisms (most notably, inverse Compton scattering) are inefficient at such large energies (Aharonian 2004, Gabici & Aharonian 2007).

According to a widely accepted (but not proven) picture, CRs are accelerated at supernova remnant shocks via first order Fermi mechanism (Drury 2012). However, the acceleration of CR protons up to PeV energies remains a challenge for theoretical models of supernova remnants (Bell *et al.* 2013). In addition to that, it is very difficult to determine observationally whether a gamma-ray source is a PeVatron or not, due to the meagre photon statistics in the multi-TeV domain. For this reason, the issue of PeV particle acceleration in the Galaxy is still open.

A breakthrough came recently, when the H.E.S.S. Collaboration (2016) anounced the discovery of the first galactic PeVatron. It is located in the very central region of the Galaxy (within the inner $\sim 10$ pc) and is most plausibly associated with Sgr A*, the supermassive black hole located at the galactic centre. This discovery has a strong impact on the discussion about the origin of CRs, since it demonstrates that PeVatrons other than (the hypothetical) supernova remnants do exist.

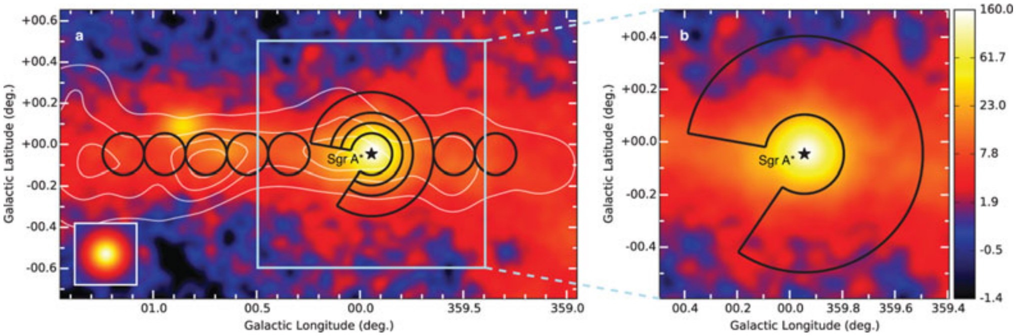

**Figure 1.** Very-high-energy $\gamma$-ray image of the Galactic Centre region as seen by H.E.S.S. The colour scale indicates counts per $0.02^\circ \times 0.02^\circ$ pixel. **Left panel:** The black lines outline the regions used to calculate the CR energy density throughout the central molecular zone. White contour lines indicate the density distribution of molecular gas, as traced by its CS (carbon monosulfide) line emission (Tsuboi *et al.* 1999). The inset shows the simulation of a point-like source. **Right panel:** Zoomed view of the inner $\sim$ 70 pc and the contour of the region used to extract the spectrum of the diffuse emission shown in Figure 3.

## 2. H.E.S.S. observations and their interpretation

Figure 1 shows the very high-energy gamma-ray image of the Galactic Centre (GC) region, resulting from a 10 years long observational campaign performed by H.E.S.S. (Aharonian *et al.* 2006, Aharonian *et al.* 2009, Aharonian, F. *et al.* 2004, H.E.S.S. Collaboration 2016). A diffuse very-high-energy gamma-ray emission is visible in correspondence with the Central Molecular Zone (CMZ), which contains predominantly molecular gas and extends (in projection) out to $r \sim 250$ pc at positive galactic longitudes and $r \sim 150$ pc at negative longitudes. The strong spatial correlation (although not linear, see discussion below) between gamma rays and gas points towards a hadronic origin of the diffuse emission.

The energy density of multi-TeV CRs in the CMZ is found to be roughly an order of magnitude larger than that of the sea of CRs that universally fills the Galaxy, while the energy density of low energy (GeV) cosmic rays in this region has a level comparable to it (Yang *et al.* 2015). This requires the presence of one or more accelerators of multi-TeV particles operating in the CMZ. From the angular distribution of gamma rays and the spatial 3D distribution of gas in the CMZ it is possible to derive the spatial distribution of multi-TeV CRs (Figure 2), which is consistent with the solution of the transport equation of CRs injected continuously at a constant rate $Q$ at the GC ($R = 0$) and characterised by an isotropic and homogeneous particle diffusion coefficient $D$:

$$\frac{\partial n_{CR}}{\partial t} = D \nabla^2 n_{CR} + Q \delta(R) \tag{2.1}$$

which reads:

$$n_{CR}(E, R) = \frac{Q(E)}{4 \pi D(E) R} \tag{2.2}$$

where $n_{CR}$ represents the differential energy distribution of CRs per unit volume. Equation 2.2 is valid under the condition that the source located at the GC injected CRs for a time $\Delta t$ long enough to fill with them the entire CMZ (otherwise we would observe a deviation from the $1/r$ profile derived in Figure 2). A lower limit for such time scale can be estimated by equating the CR diffusion length to the size of the CMZ ($r_{CMZ} \sim 200$

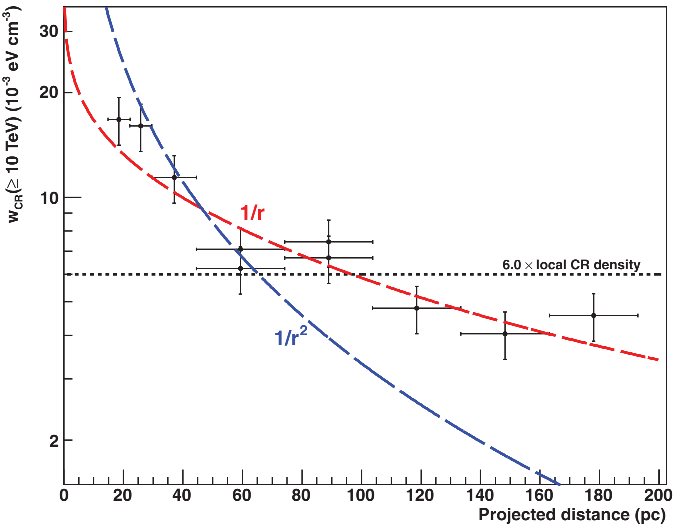

**Figure 2.** Spatial distribution of the CR density versus projected distance from Sgr A$^*$. The vertical and horizontal error bars show the $1\sigma$ statistical plus systematical errors and the bin size, respectively. A fit to the data of a $1/r$, $1/r^2$ and an homogeneous (horizontal dotted line) CR density radial profiles are shown. The best fit of a $1/r^\alpha$ profile to the data is found for $\alpha = 1.10 \pm 0.12$. Thus, the $1/r$ radial profile is clearly preferred by the H.E.S.S. data.

pc):

$$r_{CMZ} \lesssim \sqrt{6\ D(E)\ \Delta t} \tag{2.3}$$

which gives:

$$\Delta t \gtrsim 2 \times 10^3 \left( \frac{D}{10^{30}\ \mathrm{cm^2 s^{-1}}} \right)^{-1} \ \mathrm{yr} \tag{2.4}$$

where $D$ is normalised to the characteristic value of the diffusion coefficient of multi-TeV CRs in the Galactic Disk (Strong *et al.* 2007).

By fitting the data shown in Figure 2 with Equation 2.2 one can obtain $Q$ or, equivalently, the total energy injection rate of CRs at the GC:

$$W(>10\ \mathrm{TeV}) \approx 4 \times 10^{37} \left( \frac{D}{10^{30} \mathrm{cm^2/s}} \right) \ \mathrm{erg/s}\ . \tag{2.5}$$

The particle diffusion coefficient is very unknown in most astrophysical contexts, and this introduces a significant uncertainty in the estimate of the injection power. However, an upper limit for $W(>10$ TeV$)$ can be obtained after recalling that the $1/r$ profile of the CR spatial distribution is a characteristic feature of diffusive propagation. In order to be in the diffusive regime the following condition has to be satisfied:

$$\frac{R^2}{6D} \gg \frac{R}{c} \tag{2.6}$$

where $c$ is the speed of light. When the condition above is not satisfied CRs propagate ballistically rather than diffusively. Combining Equation 2.5 and 2.6 one finally gets:

$$W(>10\ \mathrm{TeV}) \ll 1.2 \times 10^{38}\ \mathrm{erg/s}\ . \tag{2.7}$$

Figure 3 shows the energy spectrum of the diffuse gamma-ray emission, which can be fitted by a power law $E^{-\alpha}$ extending with a photon index $\alpha \sim 2.3$ up to energies of tens of TeV. No indication of a cutoff or a break has been found in the spectrum, indicating

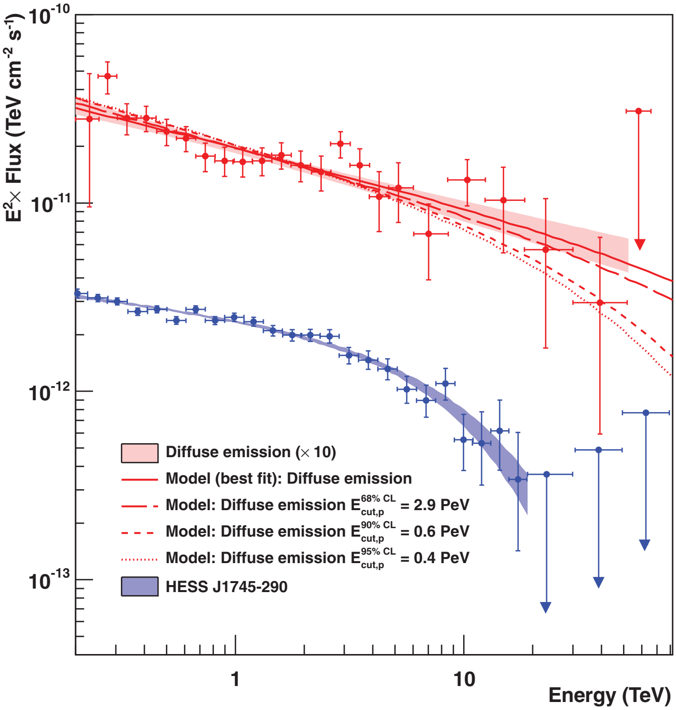

**Figure 3.** Very-high-energy gamma-ray spectra of the diffuse emission and of HESS J1745-290 (the source at the GC) in units of TeV cm$^{-2}$ s$^{-1}$. The 1$\sigma$ confidence bands of the best-fit spectra of the diffuse and HESS J1745-290 are shown in the upper and lower shaded areas, respectively. The lines show the numerical computations assuming that gamma rays result from the decay of neutral pions produced by proton-proton interactions. For the sake of clarity, the fluxes of the diffuse emission spectrum and models are multiplied by 10.

that the emission is hadronic (neutral pion decay) and that particle acceleration proceeds up to PeV energies. This is the first time that such a $\gamma$-ray spectrum is detected. The best fit to data is found for a proton spectrum following a pure power-law with index $\alpha \sim 2.4$. If the H.E.S.S. data are fitted with a power law spectrum of protons plus an exponential cutoff at an energy $E_{cut}$, then the corresponding secondary $\gamma$-ray spectrum deviates from data at 68%, 90% and 95% confidence levels for $E_{cut} = 2.9$ PeV, 0.6 PeV and 0.4 PeV, respectively. We can conclude, then, that a PeVatron is present within $\sim$ 10 pc (the H.E.S.S. angular resolution at a distance of 8.5 kpc) from the GC. The H.E.S.S. Collaboration (2016) discussed several scenarios in order to identify the most plausible site for the acceleration of PeV particles, and concluded that most likely the production of PeV particles is connected, in a way or another, to the supermassive black hole (SMBH) in the GC (Sgr A*). The H.E.S.S. Collaboration (2016) also discussed possible links between the diffuse gamma-ray emission and the GC point-like gamma-ray source (whose spectrum is shown in Figure 3). The reader is referred to that paper for more details.

If the central SMBH is indeed the source of PeV particles, then the required acceleration rate of about $10^{37} - 10^{38}$ erg/s derived in Equation 2.5 and 2.7 would exceed by two to three orders of magnitude the current bolometric luminosity of Sgr A* (Genzel *et al.* 2010). Equivalently, such luminosity can be expressed as about 1 % of the current accretion power of the SMBH. These are quite tight figures, but one has to recall that the accretion rate in the central SMBH currently is relatively modest, and that at certain epochs in the past the central SMBH, of mass $4 \times 10^6$ Solar masses, might have operated at much higher accretion rate. Thus, one can speculate that in the past the CR production rate was higher than the present one (see e.g. Istomin 2014 and references therein). In this regard it is interesting to note that an average acceleration rate of $10^{39}$ erg/s of $E$ >10 TeV protons over the last several millions years would be sufficient to explain the flux of CRs around the knee at 1 PeV. If so, this could be a solution to the problem of the origin of PeV CRs, and provide an alternative to the widely accepted paradigm of the supernova remnant origin of Galactic CRs (Cristofari *et al.* 2013, Parizot 2014). Remarkably, such an acceleration rate would also suffice to explain the flux of very-high-energy neutrinos recently detected by IceCube (Taylor *et al.* 2014).

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