The Galactic Center as a point source of neutrons at EeV energies

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The central region of our Galaxy is a very peculiar environment, containing magnetic fields in excess of 100 mG and gas densities reaching $\sim 10^4$ cm$^{-3}$. This region was observed as a strong source of GeV and TeVs gammas, what suggests that a mechanism of proton-neutron conversion could be taking place therein. We propose that the Galactic Center must also be a source of EeV neutrons due to the conversion of ultra high energy cosmic ray protons into neutrons via p-p interactions inside this region. This scenario should be falsifiable by the Pierre Auger Observatory after a few years of full exposure.

1. Introduction

Cosmic rays at the highest energies, i.e., above few $\times 10^{17}$ eV, are very likely extragalactic and pose some of the most intriguing questions of the contemporaneous research in astrophysics. Their origin, composition, acceleration and production mechanisms are still unclear [1]. The first step towards answering these questions will very likely require the unambiguous identification of an astrophysical counterpart to a subset (cluster) of events.

Despite the fact that, over wide angles on the sky, all experiments agree that the flux of ultra-high energy cosmic rays (UHECR) seems isotropic, there have been claims in the past for the detection of anisotropy on smaller scales. The unambiguous determination of the existence of this anisotropic signal in the experimental data, and its astrophysical interpretation, is a fundamental challenge in the study of ultra high energy cosmic rays (UHECR) and is not free from controversies. The AGASA experiment reported [2] an interesting result claiming a 4.5$\sigma$ excess at energies in the vicinity of $\sim 10^{18}$eV. Although AGASA was located in the Northern Hemisphere and the Galactic Center was out of its field of view, the anisotropy signal was located at low galactic latitudes and seemed to point to the general direction of the Galactic Center. This was the most significant, but not the only evidence in favor of some cosmic ray flux excess associated with the Galactic plane. In fact, Flys Eye data [3] also showed some anisotropy related to the Galactic plane in a similar energy interval: $4\times 10^{17} - 10^{18}$ eV, although not claim was made of a relationship with the Galactic Center. A little later, the AGASA anisotropy received further support from a reanalysis of data from SUGAR [4], which did have the Galactic bulge inside its field of view, and found a possible point-like excess compatible with the AGASA signal. However, and rather surprisingly from a theoretical point of view, the SUGAR point-signal was not located at the Galactic Center itself, but at $\sim 10^\circ$ from that position, making any astrophysical interpretation difficult, since that result excluded the most obvious candidate, the Galactic supermassive black hole, as a possible source [5]. Recently, an analysis using data from the Pierre Auger Observatory [6,7], which has the Galactic Center well inside its field of view and has already doubled the AGASA exposure, does not support the AGASA anisotropy result. It must be noted that Auger has already collected four times more
events than AGASA in the same energy interval and angular window.

The later Auger result, strengthen by HiRes data that also points into the same direction (see a HiRes article in this Proceeding), seems to rule out the AGASA claims. However, it does not rule out the Galactic Center as a source of EeV cosmic rays. In fact, in this work we will present an almost unavoidable scenario for the generation of anisotropy in the cosmic ray signal associated with the inner regions of our Galaxy. It is based not on a hypothetical Galactic accelerator, but on well known characteristics of the extragalactic flux of high energy particles and of the interstellar medium (ISM) in the Galactic Center instead. Essentially, the large magnetic fields immersed in the very dense interstellar medium present in the inner ∼ 200 pc of the bulge, partially trap the known extragalactic cosmic ray flux diffusing into the region and converts into neutrons a sizable fraction of it. We will also show that the outgoing neutron flux should be seen as a point source located at the Galactic center. This neutron source should be observable, at an acceptable level of statistical significance, during the lifetime of the largest cosmic ray experiments like, in particular, the Pierre Auger Observatory.

After a brief review of those characteristics of the Galactic Center that are specially important for this work, we proceed to estimate of the neutron production mechanism. Our results are conclusions are confirmed through analytical, semi-analytical and detailed Monte-Carlo calculations based on the proposed scenario. Finally, we also discuss the statistical significance of the calculated signal for particular case of the Pierre Auger Observatory.

2. The Galactic Center

The center of our Galaxy is a very peculiar region permeated by magnetic fields in excess of 100 mG that encompasses a very high density molecular zone. Gas densities in the interstellar medium can reach up to ∼ 10^4.5 cm^-3 measured at the galactic plane. This high density, high filling factor region, is denominated Central Molecular Zone (CMZ). The transition to conditions more typical of the galactic disk occurs at a galactocentric distance of ∼ 200 pc.

The magnetic field structure inside the CMZ can be observed or inferred using several techniques. The morphology and intensity can be obtained from infrared polarimetry, Zeeman effect and radio synchrotron emission data. Those observations demonstrate that there are at least two distinct regular components, besides the turbulent one, forming the global magnetic field that permeates the inner 400 pc of our Galaxy. One of the regular magnetic components is perpendicular to the galactic plane and is mainly traced by long filaments of radio emission, denominated non-Thermal radio filaments. The magnetic field inside those filaments seems to reach values of the order of some few ×10^3 µG [10]. Their morphology suggests that they could be part of a poloidal component of the global magnetic field, and the fact that one can find those filaments basically anywhere inside the region can lead to the conclusion that they could be tracing a large-scale poloidal field, rooted in a central dipolar moment, that affects scales comparable to the size of the whole CMZ. A second component is revealed in polarization data [11], where magnetic field vectors parallel to the galactic plane are clearly seen. Those observations suggest that the Central Molecular Zone is in fact filled by large-scale toroidal magnetic field, with a global intensity of some few ×10^2 µG.

Therefore, the field inside the 400pc of our galaxy is between 2 and 3 orders of magnitude larger than in the neighboring Galactic plane and is remarkably well structured inside the CMZ. The regular component is a composition of poloidal and toroidal/radial contributions. Inside Galactic Center there are regions where either...
component is dominant, and the combination of those components strongly suggests a existence of an A0 dynamo operating inside the CMZ.

3. Neutron production in the Galactic Center

The large intensity of the magnetic field (100µG-3mG) inside a galactocentric distance of ∼200 pc, increases by a large factor de crossing time of incoming particles of the high energy extragalactic cosmic ray flux. Since the density is also very large inside the CMZ, the trapped particles traverse a much larger amount of matter than they would otherwise while crossing the regular interstellar medium that characterizes the rest of the Galactic plane [15].

Thus, the Galactic Center environment could be an efficient conversion region, where charged protons from the extragalactic cosmic ray flux could be transformed into neutrons through hadronic interactions taking place therein. The principal process should be the reaction \( p + p \rightarrow n + p + N\pi \) which, besides a neutron source, would lead to the production of a high energy \( \gamma \)-ray source from the \( \pi \)-decay channels.

In particular the observed magnetic field intensity and spatial scale could be capable of partially entrapping protons with energies as high as \( 10^{19} \)eV, but with a greater efficient in the < 10 EeV energy range. In addition, this is the energy a neutron should have in order to arrive at the solar circle since, in the laboratory reference frame, the mean distance it travels before decaying is \( d_{n,\text{pc}} = 8 \times E_{\text{EeV}} \), which is comparable with the distance between the Sun and the Galactic center. Thus, mean life time of the neutron helps to tune the optimum energy to observe the Galactic Center neutron source at \( \lesssim 1 \) EeV, since lower energy particles, although being more numerous in the cosmic ray flux and being more efficiently trapped in the CMZ, produce very few neutrons that are able to survive up to the Earth. Neutrons that decay on the fly transform into protons that are strongly deflected by the Galactic magnetic field and dilute away in the background cosmic ray flux [5]. It is only the surviving neutrons that give a clear, point-like signal that might be eventually observable with existing experiments.

4. Numerical simulations

In order to calculate the corresponding neutron flux at Earth, we developed a Monte-Carlo computer code to propagate particles in the Galactic Center region with the observed matter and magnetic field distributions. Those particles were injected randomly at the boundary of the region, assumed to be a sphere centered in Sgr A, with a radius of 200pc. The direction of the momenta of the injected particles at the boundary was also chosen randomly under the further assumption of an isotropy cosmic ray flux at energies around 1 EeV.

The intensity of the magnetic turbulence inside the CMZ is not well established from observations at present. Therefore, in order to assess the role of the uncertainty in the magnetic field turbulence on the dynamics of cosmic rays in the ISM of the confinement region, we perform simulations with three different field models: (i) purely turbulent, (ii) purely regular and (iii) an intermediate case, with \( \langle B_{\text{turb}} \rangle / \langle B_{\text{reg}} \rangle = 1 \). In all models, the turbulence was generated as a superposition of plane waves packets, with a Kolmogorov power spectrum.

Since there is a considerable amount of mechanical energy being injected at the center of the region by the several observed supernova remnants, the approximation used to model the regular component of the magnetic field inside the CMZ, was inspired on the Heliospheric magnetic field and it was obtained by the combination of three contributions: (i) a dipole, (ii) a dynamo component resultant of a current system that propagates radially outward along the equatorial plane and closes meridionally over the spherical boundary of the CMZ and the Galactic polar axis, and (iii) a radial component resultant from a ring current over the Galactic plane.

The different realizations of the total magnetic field were normalized in such a way as to reproduce the average energy density observed inside the CMZ.

The propagated particles, protons in the resent work, were also allowed to interact hadron-
ically with the ambient ISM. Hadronic interactions were treated using the model Sybill 2.1 [13]. At this stage, only surviving protons and neutrons were tracked. After their production, neutrons are propagated through the ISM out of the CMZ, where they can undergo further interactions with the ISM. From the external border of the region up to the Earth, spallation reactions with the ISM are neglected, and only decay is considered in the model.

5. Neutron conversion efficiency

We can estimate the neutron flux that is leaving the Galactic Center from very general arguments. First we estimate the factor $f$ by which the time that a particle spends inside the confinement region increases when compared to the free-fly crossing time. This factor can be written as $f \sim \Delta t / \tau_L \sim cL / D$, where $\Delta t \approx L^2 / D$ is the characteristic diffusion time through a region of size $L$ and diffusion coefficient $D$, and $\tau_L$ is the light travel time through that same region.

The total mass traversed by the particle in the region, $\Lambda$, can be written in terms of the diffusion coefficient:

$$\Lambda \sim f \times m_p \times \langle n_{ISM} \rangle \times L_{GC}$$

(1)

where $\langle n_{ISM} \rangle$ is the average matter density (e.g., as estimated from the radio emission data) and $L_{GC}$ is the transversal scale, respectively, of CMZ. Taking takes, as an order of magnitude estimate, $L_{GC} \sim 200$ pc and densities varying typically between $10^{4.5}$ and $10^3$ cm$^{-3}$ inside the confinement region, one obtains $\Lambda \sim 1 - 10 \times f$ g/cm$^2$ which, considering that the mean free path of protons in the ISM is $\lambda_{pp} \approx 40$ g/cm$^2$, already gives an idea of the relevance of the phenomenon.

Using the simulation code described in Section 4 we propagated particles at $10^{18}$ eV in a purely turbulent magnetic field and in a composite field, in order to calculate an effective diffusion coefficient ($D_{eff}$) for cosmic rays crossing the region. From those simulations we obtained a volume averaged value of $D_{eff}^{turb} \sim 4.6 \times 10^{26}$ m$^2$/s for the purely turbulent scenario and $D_{eff}^{mix} \sim 6.1 \times 10^{26}$m$^2$/s for the mixed field scenario.

Therefore, the total mass traversed by a typical cosmic ray proton at 1 EeV would be $\Lambda_{SA,turb} \sim 58$ g cm$^{-2}$ for a pure turbulent magnetic field, and $\Lambda_{SA,mixed} \sim 45$ g cm$^{-2}$ for a mixed field. Therefore, considering a proton-proton interaction length $\lambda_{pp} \sim 40$ g cm$^{-2}$, we see that $\sim 80\%$ of the protons entering the region should experience, on average, one interaction in the purely turbulent case, and $\sim 70\%$ in the mixed field. Since the multiplicity for neutron production in p-p reactions is $\sim 1/4$, the neutron production efficiency per incoming proton can be estimated as $\Psi^{n/p} \sim 1/4 \times (1 - e^{-\Lambda/\lambda_{pp}})$, so for both models of the magnetic field, we have $\Psi^{n/p}_{SA,turb} \sim 0,19$ and $\Psi^{n/p}_{SA,mix} \sim 0,17$ for the pure turbulent and mixed fields respectively.

The previous result can be checked using the Bohm diffusion approximation, $D_{Bohm} \sim \frac{1}{3} \tau_L c \sim 3 \times 10^{25} m^2 s^{-1})$. Furthermore, taking into account that the simulations point to an effective diffusion length of the order of $0.10 \times L_{GC}$, the traversed mass is $\Lambda_{Bohm} \sim 90$ g cm$^{-2}$, the resultant neutron production efficiency is $\Psi^{n/p}_{Bohm} \sim 0,22$.

Table 1 shows, on the other hand, the neutron production efficiency per injected proton into the CMZ.

| Field     | $\Psi^{n/p}_{MC}$ | $\sigma$ |
|-----------|------------------|---------|
| Reg.      | 0.38             | $2 \times 10^{-3}$ |
| Mixed     | 0.28             | $2 \times 10^{-3}$ |
| Turb.     | 0.16             | $4 \times 10^{-4}$ |

Table 1 shows that the purely regular magnetic field is the most efficient for neutron production. This characteristic was already expected since, in this kind of field structure, a large fraction of particle orbits repeatedly crosses high density regions, inducing neutron conversion. This can be appreciated in figure 1 that, even for the mixed field scenario, shows that neutron conversion takes place preferentially at a ring surround-
ing the Galactic plane near the external region of the CMZ.

\[ J_{n,GC}[s^{-1}] \approx 2\pi \Psi^{[n/p]} J_{RC,extgal} \times A_{GC} \quad (2) \]

where \( J_{RC,extgal} \) is the extragalactic cosmic ray flux, \( \sim 10^{-33.5} cm^{-2}s^{-1}sr^{-1}eV^{-1} \) at \( 10^{18}eV \), and \( A_{GC} \) CMZ boundary surface area.

So, the neutron flux arriving at a detector at Earth subtending a solid angle \( \Omega \), can be written as:

\[ J_{n,\text{det}}[s^{-1}] \approx J_{n,GC} \frac{\Omega^{sr}}{4\pi} \quad (3) \]

However, it is necessary to take into account at least three main suppression factors. The first is that neutrons are unstable and some fraction of them decay on the fly between Earth and the Galactic Center. Taking \( t \) as the flying time to earth, and \( \tau \) as their mean life, this factor can be written as:

\[ F_{\text{dec}} = e^{-t/(\gamma \tau)} \sim 0,5 \]

The second factor is due to the fact that protons generating neutrons at \( 10^{18}eV \) must have an energy larger than \( 10^{18}eV \). Therefore, the flux of protons entering the Galactic Center is smaller than the one previously considered by a factor that is proportional to the energy. Nonetheless, it is important to note that the increase in the proton energy is not significantly high to either alter the simulation dynamics in the production region or modify considerably the reaction cross sections.

We can calculate this suppression factor by taking into account that the cosmic rays flux at this spectral region is a known power law, \( J(E) \propto e^{-2.7} \), and that the average neutron-to-proton energy ratio in the \( pp \rightarrow n \) reaction can be written as:

\[ \frac{\langle E_n \rangle}{\langle E_p \rangle} = \int_0^1 xg(x)dx = \int_0^1 3x(1-x^2)dx \]

where \( g(x) \) is the nondimensional inclusive cross-section \[14]. So we can write this suppression factor due to the smaller flux of higher energy protons as:

\[ F_{\text{HEP}} = \frac{N(E_n)}{N(E_p)} = \left( \frac{\langle E_n \rangle}{\langle E_p \rangle} \right)^{2.7} \sim 0.5 \]
The third suppression factor is due to the detection characteristics of the Pierre Auger Observatory at $10^{18}$eV. As the observatory is optimized for a higher energy range, at energies of $\sim 10^{18}$eV, not all impinging cosmic rays are detected. This factor is:

$$F_{PAO} \sim 0.5$$

Therefore, the total suppression flux factor is:

$$F_{Sup} = F_{dec} \times F_{HEP} \times F_{PAO} \sim 0.1$$

which means that only $\sim 10\%$ of the neutrons emitted at the Galactic Center, should be detected at Earth. Thus, using equations 2, 3 and 4, we estimate in table 2 the neutron flux detected at the Pierre Auger Observatory in the energy interval $1 - 2 \times 10^{18}$eV.

Table 2

| Field | Flux (n/year) |
|-------|--------------|
| Regular | 39 |
| Mixed | 29 |
| Turbulent | 17 |
| Analytical (Bohm) | 23 |
| Semi-analytical (Mix.) | 18 |
| Semi-analytical (Turb.) | 20 |

An important result in Table 2 is the fact that, the estimated number of neutrons per year inside the solid angle subtended by the CMZ is rather independent of the assumptions made on the field structure and, furthermore, is comparable with the expectations obtained from simple analytical and semi-analytical approaches.

7. Signal statistical significance

The statistical significance of the neutron signal can be calculated using the method firstly proposed by Li&Ma in [16] for $\gamma$-ray astronomy. Thus,

$$S = \frac{J_{src}}{\bar{J}(J_{src})} = \frac{J_{src}}{\sqrt{J_{sgn} + \alpha^2J_{bg}}}$$

where $J_{src}$ is the flux solely from the source, $J_{bg}$ is the background flux, $J_{sgn}$ is the total measured flux (source+background), $\tau$ is the integration time and $\alpha$ is the fraction of time that the detector observes the source.

Therefore, assuming that when the Galactic Center is not in the sky there is no other point source at those energies, that all the received signal is background (i.e., the extragalactic cosmic ray flux) when the neutron source is not on the sky, and taking into account the previously calculated fluxes for the source at the Galactic Center, the integration time necessary for the full Pierre Auger Observatory to detect the neutron source with a given statistical significance. The results, for all the magnetic field models considered in this work, are presented in figure 2, where it can be seen that the the Galactic Center should be detectable as a point source with at least $2.0 \sigma$ in 10 years of the complete array operation, independently of the chosen magnetic field model. Furthermore, in the more likely case of a mixed field scenario, 5 years should be enough for a detection at $2.5\sigma$.

Figure 2. Statistical significance of the neutron signal as a function of integration time for the full Auger detector.
Additionally, a future space experiment like EUSO, with at least $\sim 10^5 \text{ km}^2$ of effective area, should be able to detect this neutron source in less than 2 years at $> 8.5\sigma$.

8. Conclusions

Based on rather simple arguments and very general analytical and semi-analytical calculations, as well as on detailed Monte Carlo simulations, it was demonstrated that the Central Molecular Zone inside the inner 200 pc of our Galaxy should act as a source of neutrons at EeV energies. Furthermore, this source should be detectable by the Pierre Auger Observatory within 3-10 years, independently of the actual magnetic field structure present in the CMZ, at a statistical significance between 2.0 and 4.5 $\sigma$ in the energy interval $1 - 2 \times 10^{18} \text{eV}$. This is a lower limit, since only p-p interactions were considered, despite the fact that p-$\gamma$ interactions could also give a sizable contribution due to the large infrared background present in the region. An independent test to the actual existence of this source would be the detection of TeV gamma radiation consistent with the p-p interaction rate expected due to partial trapping of cosmic ray protons inside the CMZ. Detail estimates of this flux component are under way. This could help explain the $\gamma$-ray emission detected by the H.E.S.S. collaboration [12].

The Galactic center neutron source could be the first high energy point cosmic ray source. This neutron source could be useful as a calibration standard for extensive air shower reconstruction techniques because of its well defined location on the sky. Additionally, its detection would enhance our present understanding of the Galactic Center environment.

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