Sgr A East as a high energy neutron and neutrino factory in the galactic centre

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Abstract. Sgr A East is a supernova remnant located few parsecs away from the Galactic Centre (GC). There are good reasons to believe that this object is the source of the gamma-ray excess detected by HESS in the direction of the GC meaning that Sgr A East is likely to be an efficient Cosmic Ray (CR) accelerator. This source is embedded in a dense gas environment and an IR background which may act as astrophysical beam dump where secondary photons, neutrinos and neutrons can be produced. In particular, if $^4$He nuclei are accelerated beyond the EeV in Sgr A East, neutrons with energy close to the EeV should be produced by the photodisintegration of these nuclei onto the thick IR background. Neutrons with such an energy can reach the Earth before decaying and may be detectable under the form of a CR point-like excess in the direction of the GC. We determined the expected energy spectrum and the amplitude of this signal showing that it may be measurable by the AUGER observatory. Using the HESS data to normalise the primary proton spectrum, we also estimated the expected neutrino signal produced by secondary pion decay for ANTARES and for a forthcoming Mediterranean km$^3$ neutrino telescope.

1. Introduction

Due to the coincidence of the CR energy in the Galaxy with the energy released from galactic SuperNovae (SN), it is generally accepted that the majority of CRs in our Galaxy are accelerated in the supersonic outflow of SN. The recent observation of gamma-ray emission above the TeV from several SNRs is providing further support to this paradigm [1]. However, a final proof that the primary particles giving rise to this radiation are nuclei is still missing. Furthermore, the maximal energy reached in these astrophysical accelerators is unknown. In principle this energy could be as large as few EeVs which would explain the continuity of the CR spectrum up to the ankle ($E \approx 6$ EeV). Since, even at energies beyond the EeV, electrically charged CRs are significantly deflected in the galactic magnetic field, the only messengers which may keep the angular correlation with the source and provide a proof of their hadronic origin are neutrinos and very high energy neutrons. Interestingly, neutrons with an energy close to the EeV have a large probability to reach the Earth from a source at typical galactic distance (1 – 10 kpc). Although high energy neutrons and protons give rise to indistinguishable showers in the atmosphere, a galactic neutron source may be recognised by the extensive air shower experiments under the form of a localised excess of CRs with energy $\gtrsim 1$ EeV.
The SNRs which are the most promising sources of EeV neutrons are those residing in the densest regions of the Galaxy, where strong magnetic fields as well as thick radiation and gas targets can presumably be found. Active SNRs in the proximity of the GC and/or in the nearby of dense molecular clouds are natural candidates to the role of EeV neutron and neutrino factories. A particularly interesting SNR in that region is Sgr A East [2]. Detailed X-ray observations, performed mainly by the Chandra observatory [3], allowed to establish that this is the remnant of a single type II SN explosion which took place about $5 \times 10^4$ years ago (the light propagation time is subtracted) less than 3 pc away from the GC, i.e. at a distance of 8 kpc from the Earth. The explosion released about $10^{51}$ erg in the form of kinetic energy of the ejecta. This SNR is embedded within a dense ionised gas halo and in a background of Infrared (IR) radiation due to dust emission at the temperature $T \sim 40$ K [4]. Furthermore, the expanding Sgr A East radio shell is interacting with a dense molecular cloud. Strong magnetic fields, as large as few mG, have been observed in that region [5] which may allow the acceleration of nuclei up to ultra-high energies ($E > 10^{18}$ eV).

A $\gamma$-ray emission has been also recently observed by the HESS Cherenkov telescope in the direction of the GC [6]. Although the limited angular resolution reachable by HESS (about 1' corresponding to 2.3 pc at the GC distance) did not allow a firm identification of the source of this emission, several arguments point to Sgr A East as the most plausible source. The most convincing among these arguments is based on the energetic of the emission observed by HESS. Indeed, in [7] we showed that by assuming that the CRs in Sgr A East are shock accelerated with a 1% efficiency, the $\gamma$-ray flux expected from the decay of neutral pions produced in the hadronic collisions of the CR with the surrounding gas practically coincides with that measured by HESS. As a consequence, a neutrino flux comparable to the gamma-ray flux observed by HESS is also to be expected. Composite nuclei should be accelerated along with protons with the same spectral slope. We will show that if the spectrum of $^4$He nuclei extends steadily up to few EeV their photo-disintegration onto the IR radiation in the GC should give rise to a neutron flux which may be detectable by AUGER.

2. High energy neutrons from nuclei photo-disintegration

High energy nuclei can be effectively dissociated into lighter nuclei and one, or more, nucleons when colliding with photons. If the centre of mass energy is larger than few MeV and smaller than $\sim 30$ MeV the photo-disintegration (PD) can take place in the giant dipole resonance regime giving rise either to a single free nucleon or at most to a pair of free nucleons, each carrying a fraction $1/A$ of the primary nucleus energy, where $A$ is the nuclear weight. This is indeed the regime of interest in the present context. In fact, since the Lorentz factor required to produce EeV neutrons is $\gamma^* \sim 10^{18}$ eV/$m_n \sim 10^8$, and the mean energy of thermal photons with $T \sim 40$ K is $\epsilon \sim 10^{-2}$ eV, the corresponding c.m. energy is $\gamma^* \epsilon \sim 1$ MeV.

In [7] we applied the general results found in [8, 9] to determine the PD rate of ultra-relativistic nuclei in the environment of Sgr A East. For all the most abundant species generally present in a type II SNR ($^4$He, $^{12}$C, $^{16}$O, $^{56}$Fe) the PD rate peaks approximatively at the same value of the product of the Lorentz factor with the photon background temperature, namely, $\gamma kT \approx 4$ MeV, corresponding to the energy $E_A^{\text{peak}} \simeq A \times 10^{18} \left( \frac{T}{40 \text{ K}} \right)^{-1}$ eV. The maximal value of the PD rate, however, varies for the different nuclear species and, in several cases, it exceeds the inverse of the SNR age. It is important to observe that when this happens further acceleration of a given nuclear species is inhibited by the PD losses. We found that, among the most abundant species expected to be present in Sgr A East, only the $^4$He can reach the energy sufficient to produce EeV neutrons. We chose the nuclei spectrum normalisation and slope to match HESS observations. Under these hypothesis we found that the differential neutron flux reaching the
Earth from Sgr A East should be
\[
\frac{dF(E_n)}{dE_n} \approx 4 \times 10^{-27} \left( \frac{R_A(E_n,T)}{10^{-12} \text{ s}^{-1}} \right)^2 \left( \frac{d}{8 \text{ kpc}} \right)^2 \left( \frac{T}{40 \text{ K}} \right)^3 e^{-\frac{d m_n}{E_n c \tau_n}} \left( \frac{A E_n}{1 \text{ EeV}} \right)^{-2.2} \text{ GeV}^{-1} \text{cm}^{-2} \text{s}^{-1}.
\]
(1)

The Pierre AUGER Observatory is an Extensive Air Shower detector under construction in Argentina [10] and already taking data. When completed the acceptance of this instrument will be \( A \Omega \approx 4700 \text{ km}^2 \text{sr} \), for a zenith angle \( \theta < 45^\circ \) with an angular resolution at energies around the EeV of about 2\(^\circ\). The geographical position of AUGER is ideal for observing a UHECR excess in the direction of the GC and the research of a flux excess in the direction of the GC was already undertaken [11]. Looking for a point-like excess the isotropic background of ordinary CRs gives rise to an unavoidable noise. We estimated the background event rate in the energy range \( 4 \times 10^{17} < E < 6.3 \times 10^{18} \text{ eV} \) incident onto the expected AUGER angular bin and compared it with the expected neutron flux from Sgr A East produced by \(^4\text{He}\) nuclei PD given in (1)
\[
\dot{N}_{\text{PD}} \simeq 130 \text{ yr}^{-1}, \quad \dot{N}_{\text{CR}} \simeq 440 \text{ yr}^{-1}.
\]
(2)
Since the expected signal is a sizeable fraction of the background, a significant excess should be detectable in the direction of the GC. The present upper limit on the CR anisotropy in the direction of the GC released by the AUGER collaboration [11] is still compatible with the neutron flux predicted in [7].

3. Neutrinos from Sgr A East
High energy neutrinos should be produced in Sgr A East by the decay of charged pions and muons generated in the hadronic scattering of the primary nuclei (mainly protons) onto the dense ionised, atomic and molecular hydrogen gas present in that region. Since, as we motivated in the Introduction, we expect the \( \gamma \)-ray flux to be dominated by photons produced by \( \pi^0 \) decay, the total neutrino flux can be directly related to the observed high energy \( (E > 0.1 \text{ TeV}) \) photon flux (see e.g. [12]). Indeed, it can be showed that, if the primary proton spectrum is a power-law with slope ~ −2, the differential neutrino flux is \( F_\nu(E_\nu = E_\gamma) \simeq F_\gamma(E_\gamma) \) [13, 14]. Due to neutrino vacuum oscillations, the flux arriving to the Earth is equally shared over all lepton families (including anti-neutrinos). Unfortunately, this flux is too low to be detectable by ANTARES [15] (giving rise to an event every 15-20 years) and hardly detectable also by a km\(^3\) water Cherenkov detector (less than 1 event per year).

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