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Checkmate: Can cosmic rays explain the high ionisation rate in the Galactic Centre?

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The ionisation rate in the Central Molecular Zone has been measured using various methods along many lines of sight. The estimated value is approximately $2 \times 10^{-14}\,\mathrm{s}^{-1}$, which is 3-4 orders of magnitude higher than the local ionisation rate. Due to the high gas column densities, cosmic rays are assumed to be the main ionising agents in the Galactic Centre. Does this unusually high ionisation rate then reveal an equally high cosmic-ray density in this region? This excess is, however, not reflected in the gamma-ray emissions. In this work, we explore the Galactic Centre ionisation scenario in which cosmic rays are the exclusive ionising agents and infer the particle injection conditions that need to be satisfied. In the case of both protons and electrons, the injection in low energies needs to be very steep (spectral index in momentum above 5.0). Moreover a huge part of the power in cosmic rays available in the entire galaxy needs to be injected in the central 100 parsecs of the galaxy. We conclude that cosmic rays can not be the only ionising agents in the Galactic Centre.

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1. Introduction

The region of interest is a cylinder of radius 120 pc and height 90 pc centered around the supermassive black hole Sagittarius A* which is embedded in the Central Molecular Zone (CMZ). The cosmic-ray (CR) ionisation rate of H_2, defined as the rate of production of H_2^+, can be written as:

$$\zeta_p(H_2) = \int_I^{E_{max}} f_p(E) v_p [1 + \phi_p(E)] \sigma_p^{ion}(E)\, dE + \int_0^{E_{max}} f_p(E) v_p \sigma_p^{e.c.}(E)\, dE \quad (1)$$

$$\zeta_e(H_2) = \int_I^{E_{max}} f_e(E) v_e [1 + \phi_e(E)] \sigma_e^{ion}(E)\, dE \quad (2)$$

where f_k is the CR spectrum of species k (number of particles per unit energy per unit volume), v_k is the particle velocity, σ_p^{ion} [1], σ_e^{ion} [2] and $\sigma_p^{e.c}$ [3] are cross sections for ionisation by impact of protons, electrons and by electron capture respectively and $\phi_k(E)$ [4] is the number of secondary ionisations produced per primary ionisation by CR particle of species k. The quantity is integrated over the particle kinetic energy E ranging from the H_2 ionisation potential $I = 15.603$ eV to $E_{max} = 100$ GeV.

The behaviour of CR particles can be described by the transport equation:

$$\frac{df_{CR}(r,p,t)}{dt} = Q_{CR}(r,p) - \frac{1}{p^2}\frac{\partial}{\partial p}(p^2 \dot{p} f_{CR}) + \frac{D(p)}{r^2}\frac{\partial}{\partial r}\left(r^2 \frac{\partial f_{CR}}{\partial r}\right) \quad (3)$$

where r is the spatial coordinate, p is the particle momentum, f_{CR} is the CR spectrum and Q_{CR} is the CR injection spectrum assumed to be continuous from a point source in the centre. Both quantities are expressed as power-laws in momentum ($f_{CR} \propto p^{-\alpha}$, $Q_{CR} \propto p^{-\beta}$). The two other terms on the right hand side are respectively the energy loss term and the diffusion term. The energy loss rate is calculated with the loss functions given in [5]. In the case of CR protons, we consider ionisation and proton-proton interaction losses. In the case of electrons, we consider losses from ionisation, Bremsstrahlung and synchrotron radiations and inverse Compton scattering. The diffusion only depends on the particle momentum: $D(p) = 10^{30}\left(\frac{p}{1\,\mathrm{PeV}}\right)^{0.3}$ cm^2 s^{-1}.

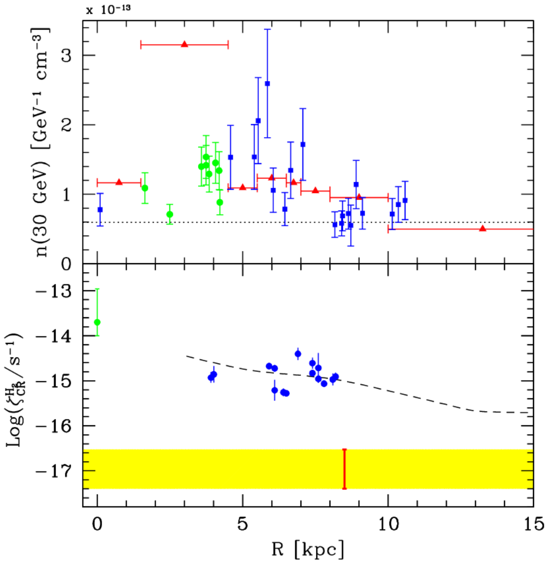

Figure 1: Radial distribution of CRs, figure from [6] **Top:** Normalisation of the CR proton spectrum at 30 GeV as a function of Galactocentric distance as derived by gamma-ray observations. Data from [7] (red), [8] (green) and [9] (blue), AMS-02 [10] (dotted line). **Bottom:** CR ionisation rate versus Galactocentric distance. Data from [11] and [12] (green), [13] (blue), local value from [14] (yellow region), renormalised profile predicted by [15] (dashed line). The red bar shows the position of the Sun.

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The ionisation rate in the CMZ has been measured using different methods by [12], [16], [17], [18] and [11] along several lines of sight (Fig.1). The estimated value is approximately $2\times10^{-14}\mathrm{s}^{-1}$. This value is higher by 3-4 orders of magnitude than the local ionisation rate $\zeta_{loc} \sim 10^{-17}\mathrm{s}^{-1}$, also known as the Spitzer value. Due to the high gas density of this region, CRs are assumed to be the main ionising agents as any ionising radiation would be absorbed. The unusually high ionisation rate would then imply an equally high CR density in this region. However, this excess is not reflected in the gamma-ray emissions and hence not in the CR proton spectra (see top panel in Fig.1) which vary across the galaxy by at most a few factors. The CR density must be boosted only at low energies. In this study we derive the enhancement needed to explain the observed ionisation rates. We then discuss the plausibility of such spectra.

2. Ionisation by cosmic-ray protons

While low-energy cosmic-ray protons (LECRp) mainly ionise the surrounding medium, high-energy cosmic-ray protons (HECRp) interact with ambient protons and produce the observed gamma rays through neutral pion decay. We use the gamma-ray flux observed in the CMZ to derive the underlying HECRp spectrum (Fig.2), using the parametrisation given in [19]:

$$\Phi_\gamma(E_\gamma) = 4\pi n_H \int \frac{d\sigma}{dE_\gamma}(E_p, E_\gamma) J(E_p)\, dE_p \tag{4}$$

where n_H is the hydrogen number density, E_p and E_γ are the proton kinetic energy and gamma-ray energy respectively, $\frac{d\sigma}{dE_\gamma}$ is the differential cross-section for gamma-ray emission from p-p collisions and J is the CR proton intensity such that $J(p) = \frac{v}{4\pi} f_p(p)$.

The parameters for the CR proton injection spectrum (Tab.1) are derived by fitting the gamma-ray emissivity using the above expression.

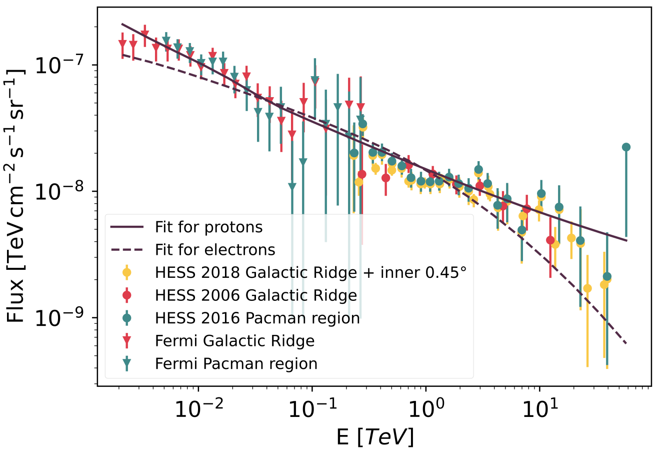

Figure 2: Fit for gamma-ray flux from the Galactic Ridge ($|\ l\ | < 0.8°$, $|\ b\ | < 0.3°$) using expected γ-ray spectrum from p-p interactions. Data from [20], [21], [22] and [23].

CR	p	e^-
$Q_{0,CR}$ (MeV^{-3} s^{-1})	1×10^5	2×10^4
β	4.2	4.2

Table 1: Fit parameters

To obtain the CR proton injection spectrum, we solve the transport equation in two different energy domains divided by the energy E^* such that in each, either losses or diffusion can be neglected. Knowing the HECRp spectrum, we access the HECRp injection spectrum. Assuming the injection spectrum is a pure power-law, the LECRp spectrum can be obtained by solving the loss equation. The two partial solutions for HECRp and LECRp can be written as:

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$$f_{HECRp}(p) = \frac{1}{V_{CMZ}} \int \frac{Q_p(p)}{4\pi D(p) r}\, dV = \frac{Q_{0,p} R_{vol}}{4\pi D_0 V_{CMZ}} \left(\frac{p}{p_0}\right)^{-\beta-0.3} \tag{5}$$

$$f_{LECRp}(E) = \frac{1}{\dot{E}} \left(\int_E^{E^*} Q_p(E')\, dE' + \dot{E}^* f_p(E^*) \right) \tag{6}$$

where Q_p is the CR proton injection spectrum in CR protons, R_{vol} is the integral over the CMZ volume of $1/r$, V_{CMZ} is the volume of the CMZ.

A complete spectrum can be obtained by patching up f_{HECRp} and f_{LECRp}. The ionisation rate for different minimum energies is calculated using this spectrum and the value never exceeds $10^{-16}\,\mathrm{s}^{-1}$. In order to enhance the spectrum without increasing the gamma-ray flux, we add an extra component to the proton injection spectrum in the low-energy domain.

As the CR injection spectrum is a power-law, we choose the enhancement to be a steeper power-law. For energies below E^* (or the corresponding momentum p^*) the enhanced injection spectrum (Δ is the spectral index of the enhancement hence $\Delta > \beta$) is the following:

$$Q_{CR,enh}(p) = \frac{Q_{CR}(p^*)}{Q_{0,CR}\left(\frac{p^*}{p_0}\right)^{-\Delta} + Q_{CR}(p^*)} \times \left(Q_{0,CR}\left(\frac{p}{p_0}\right)^{-\Delta} + Q_{CR}(p) \right) \tag{7}$$

The value of Δ which gives a spectrum capable of ionising to the observed value of ionisation rate is 5.7. The ionisation rate is plotted as a function of the minimum energy of the ionising particle (Fig.3). We have a suitable injection spectrum that can give the observed ionisation rate, but the power in CR needed to maintain such a spectrum is 10^{40} ergs/s which is very large, being equal to 10% of the total CR output of the entire galaxy.

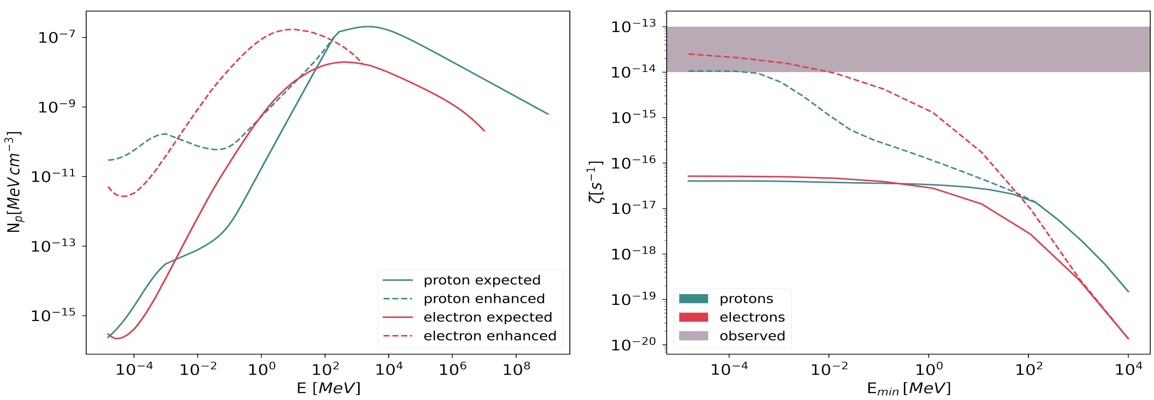

Figure 3: Left: Expected and enhanced spectra for CR protons and electrons. **Right:** Corresponding ionisation rates as a function of the minimum ionising energy.

3. Ionisation by cosmic-ray electrons

High-energy electrons produce gamma rays through non-thermal Bremsstrahlung (BR) and inverse Compton scattering (IC). Since the proportion of the observed gamma-rays that result from

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electrons is unknown, we take the observations as an upper-limit of leptonic gamma rays. We use the following descriptions by [24] and [25] to compute the gamma rays resulting from BR and IC respectively:

$$\Phi_{\gamma,Brem+IC}(E_\gamma) = c\int \sigma_{brem}(E_\gamma, E_e) f_e(E_e)\, dE_e + \int \frac{dN_{iso}}{d\omega dt}(E_e, E_\gamma) f_e(E_e)\, dE_e \tag{8}$$

where E_e is the electron kinetic energy, σ_{brem} is the BR cross-section, $\frac{dN_{iso}}{d\omega dt}$ is the interaction rate with an isotropic target photon field and f_e is the CR electron spectrum. The SED of the radiation field at $R = 1\,\mathrm{kpc}$, $z = 0\,\mathrm{kpc}$ is given in [26]. We use a superposition of two graybody emissions, each with a peak at one of the two maxima of the SED, to approximate the CMZ radiation field. The normalisation of the two graybody energy densities sets the dilution factor.

Since in the high energies, both diffusion and losses play a comparable role for electrons, we solve the full transport equation for the electrons using a simpler term for diffusion f_e/τ_{esc} where τ_{esc} is the electron diffusion time over the CMZ. The solution at all energies is the following, with $g(E) = \frac{1}{\dot{E}\tau_{esc}(E)}$:

$$f_e(E) = \frac{\int_E^\infty Q_e(E') e^{\int_{E'}^\infty g(E'')\, dE''}\, dE'}{V_{CMZ}\dot{E} e^{\int_E^\infty g(E')\, dE'}} \tag{9}$$

We assume that the injection in electrons Q_e is of the same form as for the protons and with the same spectral index. We use this steady-state solution to calculate the gamma-ray emissions from BR and IC and fit it with the gamma-ray emissivity from the CMZ (Fig.2). The fit parameters are given in Tab.1.

As the ionisation rate calculated with this spectrum isn't high enough, we use the same method as for the protons to enhance the LECRe spectrum such that the ionisation rate increases without excess gamma-ray emissions. The value of Δ for electrons is 5.0. The ionisation rate is plotted as a function of the minimum energy of the ionising particle (Fig.3). The energetic cost of maintaining such an injection spectrum for electrons in the CMZ is also approximately 10^{40} ergs/s which is huge as previously explained.

4. Conclusion

In this work, we question the assumption that CRs are responsible for the increased ionisation rate in the CMZ. It is indeed possible to reach an ionisation rate above $10^{-14}\,\mathrm{s}^{-1}$ with certain spectra if we consider particles of energies down to keV. However, the suitable injection spectra have $\beta \geq 5.0$ while most "known" CR accelerators produce CRs with much harder spectra. Either an unknown accelerator or an unknown mechanism is needed to explain such steep spectra. Most importantly, the cost of maintaining these spectra is too high - assuming a continuous injection, a power in CR particles of 10^{40} ergs/s is necessary. This represents 10% of all the power in CR in the entire galaxy, required to be present in the central $\sim$ 100 parsecs. This number is several orders of magnitude higher than the photon-luminosity of the central supermassive black-hole but isn't observable other than in the ionisation rate. Considering the reasons mentioned above, cosmic-rays should ionise the CMZ but can not be the only ionising agents.

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