PROCEEDINGS OF SCIENCE

Cosmic rays and the high ionisation rates in the Galactic Centre

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The centre of the Milky Way galaxy, approximately 8 kpc from the Earth, is a peculiar region due to its high density of stars, the resulting amount of stellar activity, and the presence of a supermassive black hole. A puzzling observation is the ionisation rate in the Central Molecular Zone which has been measured using different methods along several lines of sight. The estimated average value over this central region is 3-4 orders of magnitude higher than the local ionisation rate. As electromagnetic radiation can not penetrate the high gas column densities, cosmic rays are assumed to be the main ionising agents in this region. This unusually high ionisation rate should then reveal an equally high cosmic-ray density in this region. However, this excess is not reflected in the gamma-ray emissions that constrain the high-energy cosmic-ray spectrum. In this work, we explore the Galactic Centre ionisation scenario in which cosmic-ray protons and electrons are the exclusive ionising agents. We use a custom particle-transport simulation to model the interactions of cosmic rays with the surrounding medium and infer the necessary particle injection conditions. We find that the injection spectrum needs to be very steep. We also find that a significant fraction of the power in cosmic rays available in the entire galaxy needs to be injected in only the central 100 parsecs. We conclude that cosmic rays can not be the only ionising agents in the Galactic Centre, thereby casting doubt on a hitherto unquestioned paradigm.

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1. Introduction

The Central Molecular Zone (CMZ) is a molecular ring centered around the Supermassive Black Hole Sagittarius A*. It is modeled as a cylindrical region of height ~ 90 pc and radius ~ 120 pc. This region hosts the densest clouds in the Galaxy and a huge concentration of stars thereby becoming an exciting laboratory to understand galactic dynamics.
One important ingredient for star formation that also drives interstellar chemistry is the H_2 ionisation rate. While this process can be caused by cosmic rays (CR) or UV photons, the former is usually assumed to explain the ionisation in the CMZ. This is due to the inability of UV photons to penetrate regions of very high density. The ionisation rate in the CMZ has been estimated to be $\zeta_{CMZ} \sim 10^{-14}\mathrm{s}^{-1}$ using H_3^+ absorption spectra by [21], [10] and [11], using Herschel observations of OH^+, H_2O^+ and H_3O^+ by [14], using Meudon PDR code and H_3^+ by [19], using Fe Kα line emissions and synchrotron emissions by [31], using H_2CO temperature by [9] and using PO^+ abundance by [26]. This value is not only 3-4 orders of magnitude higher than in other regions of the Galaxy, it is also much higher than what is expected at such large column densities [24]. Although this could simply mean that the CR density is equally high in the CMZ, the gamma-ray flux from high-energy CR observed from this region doesn't corroborate this theory (Fig.1). The expected CR spectrum is then supposed to have a significant enhancement in the low-energy domain. In this study, we aim to find out if it's possible to explain the high ionisation rates with CR particles.

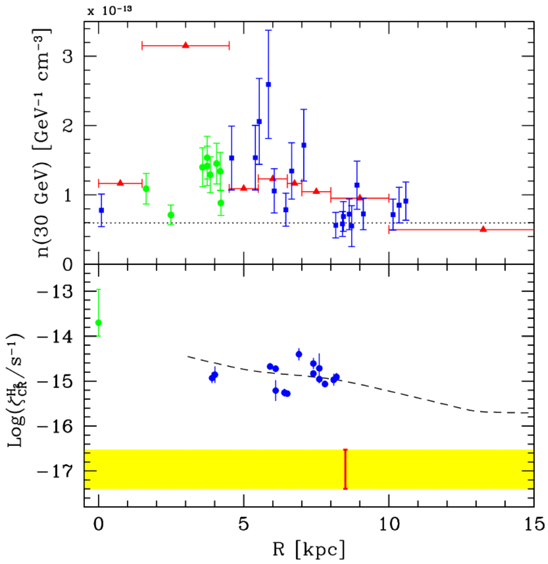

Figure 1: Radial distribution of CRs, figure from [7] **Top:** Normalisation of the CR proton spectrum at 30 GeV as a function of galactocentric distance as derived by gamma-ray observations. Data from [1] (red), [23] (green) and [4] (blue), AMS-02 [2] (dotted line). **Bottom:** CR ionisation rate versus Galactocentric distance. Data from [19] and [21] (green), [20] (blue), local value from [24] (yellow region), renormalised profile predicted by [30] (dashed line). The red bar shows the position of the Sun.

We consider the ionisation of H_2 molecules by CR protons and electrons. The different processes of H_2 ionisation are proton and electron impact (Eq.1) where "CR" can be a CR proton or electron, and electron capture (Eq.2). These are immediately followed by the production of H_3^+ ions (Eq.3). Other processes like dissociation and double-ionisation are negligible.

$$CR + H_2 \longrightarrow CR + H_2^+ + e^- \tag{1}$$

$$p_{CR} + H_2 \longrightarrow H + H_2^+ \tag{2}$$

$$H_2^+ + H_2 \longrightarrow H_3^+ + H \tag{3}$$

The cosmic-ray ionisation rate of H_2, defined by [22] as the rate of production of H_2^+, can be written as:

$$\zeta_p(H_2) = \int_I^{E_{max}} f_p(E) v_p [1 + \phi_p(E)] \sigma_p^{ion}(E)\, dE + \int_0^{E_{max}} f_p(E) v_p \sigma_p^{e.c.}(E)\, dE \tag{4}$$

$$\zeta_e(H_2) = \int_I^{E_{max}} f_e(E) v_e [1 + \phi_e(E)] \sigma_e^{ion}(E)\, dE \tag{5}$$

where f_k is the CR spectrum of species k, v_k is the particle velocity, σ_p^{ion} from [27], σ_e^{ion} from [17] and $\sigma_p^{e.c}$ from [22] are cross sections for ionisation by impact of protons, electrons and by electron capture respectively and $\phi_k(E)$ from [18] 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 CR particle injection spectrum is assumed to be a continuous power-law in the Galactic Centre. The CR steady-state spectrum f can be obtained from the injection spectrum Q by solving the CR transport equation:

$$\begin{aligned}\frac{\partial f}{\partial t} = D(p)\frac{\partial^2 f}{\partial r^2} + \frac{D(p)}{r}\frac{\partial f}{\partial r} + D(p)\frac{\partial^2 f}{\partial z^2} + \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 D_{pp}(p)\frac{\partial f}{\partial p}\right) \\ -v_w\frac{\partial f}{\partial z} + \frac{p}{3}\frac{\partial v_w}{\partial z}\frac{\partial f}{\partial p} - \frac{1}{p^2}\frac{\partial}{\partial p}\left(\dot{p}p^2 f\right) + Q\end{aligned} \tag{6}$$

where the first three terms describe the spatial diffusion of CR particles, the fourth term is the momentum diffusion of CR, the fifth and sixth terms are advection and acceleration terms, the seventh is the loss term ($\dot{p} > 0$) and finally $Q = Q_0\left(\frac{p}{PeV}\right)^{-\beta}$ is the CR injection spectrum. We use $D(p) = 10^{30}\left(\frac{p}{\text{PeV}}\right)^{0.3}$ cm^2.s^{-1}, $D_{pp}(p) = \frac{p^2 v_A^2}{9D(p)}$ ([29]) where v_A is the Alfvén velocity, $v_w = 100$ km.s^{-1} ([5]) and $\dot{p}$ is the momentum loss function that includes ionisation and p-p interaction losses for protons and ionisation, synchrotron, Bremsstrahlung and inverse Compton losses for electrons. We have designed a custom particle transport simulation using finite difference methods and operator-splitting to solve the transport equation. It is second-order accurate in time as we use the Crank-Nicolson method. We try different power-laws for the CR injection spectrum and find the corresponding steady-state spectrum using our simulation. This spectrum is then used to compute the ionisation rate for different minimum energies. The methods and results for CR protons and electrons are explained in the following before concluding on the possibility of a "cosmic-ray ionisation rate" in the CMZ.

2. Ionisation by CR protons

The CR proton density in a remote region can be inferred from the products of their interaction with the interstellar medium. High-energy CR protons interact with surrounding protons to produce gamma rays through pion decay. According to [15], the relation between the spectrum of these gamma rays Φ_γ and that of the CR protons f_p is:

$$\Phi_\gamma(E_\gamma) = 4\pi n_H \int \frac{d\sigma}{dE_\gamma}(E_p, E_\gamma)\frac{v_p}{4\pi} f_p(E_p)\, dE_p \tag{7}$$

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.

We fit the observed gamma-ray flux with the expected spectrum from a given injection spectrum (Fig.2) considering only spatial diffusion and losses. We find that $Q_{0,p} = 10^5$ MeV^{-3}.s^{-1} and $\beta = 4.2$ are the best fit parameters for the proton injection spectrum. Since this injection spectrum is obtained using the gamma-ray flux produced by protons above energy $E_p^* = 0.28$ GeV, the steady-state spectrum obtained from the injection is also valid only above E_p^*.

The main contribution to the ionisation process comes from protons below this energy. We first try extrapolating the injection spectrum below E_p^* assuming the same power-law over all energies. But the ionisation rate computed with this spectrum doesn't exceed 10^{-16}s^{-1}. We then try adding an extra component below E_p^* which is a steeper power-law of spectral index Δ. We increase Δ until the ionisation rate reaches the observed values. We find that for $\Delta = 5.7$, the ionisation rate computed with $E_{p,min} \sim 1$ keV is approximately 10^{-14}s^{-1} (Fig.3). The CR power needed for such an injection spectrum is 10^{40} ergs.s^{-1}.

The minimum ionising energy of the proton, although higher than I, is very low. The range in energy that contributes most to the ionisation rate is between 10 MeV and 10 GeV. But, increasing $E_{p,min}$ also steepens the enhancement needed to reach high ionising rates when $\Delta = 5.7$ is already much steeper than expected spectra from current CR acceleration models. Moreover, the power needed in the CMZ is 10% of the total CR power in the Galaxy.

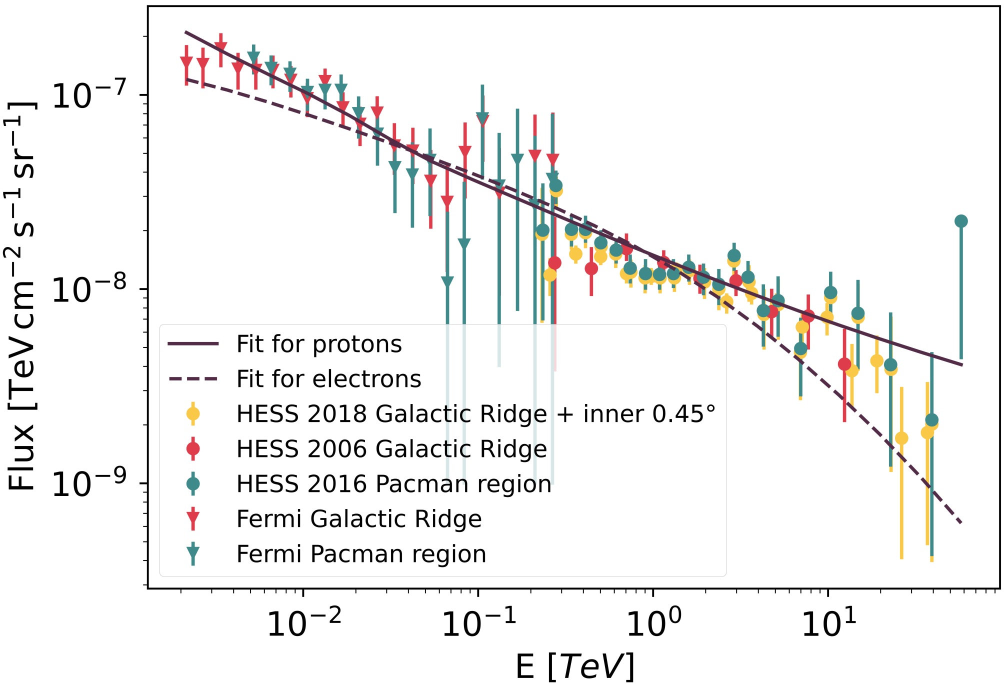

Figure 2: Fit for gamma-ray flux from the Galactic Ridge ($| l | < 0.8°$, $| b | < 0.3°$). Data from [3], [13], [12] and [8].

3. Ionisation by CR electrons

In the case of electrons, gamma rays can still be used to infer the density of CR electrons. CR electrons produce gamma rays through relativistic Bremsstrahlung and inverse Compton scattering. Following [16], the spectrum of gamma-rays resulting from IC emissions Φ_{IC} produced by an electron spectrum f_e and a seed photon field (T, κ) where T is the temperature and κ is the dilution factor, is expressed in the following way:

$$\Phi_{IC}(E_\gamma) = \int \frac{dN_{iso}}{d\omega dt}(E_\gamma, E_e, T, \kappa) f_e(E_e)\, dE_e \tag{8}$$

To obtain the seed photon field, we have modelled the expected SED at the Galactic Centre [25] as a sum of two grey-body emissions.

Following [6], the spectrum of gamma-rays resulting from relativistic Bremsstrahlung Φ_{Brem} produced by an electron spectrum f_e is as follows:

$$\Phi_{Brem}(E_\gamma) = c n_H \int \sigma_{Brem}(E_\gamma, E_e) f_e(E_e)\, dE_e \tag{9}$$

where σ_{Brem} is the related cross-section from [28].

But since observed gamma rays are almost entirely produced by CR protons, they only serve as an upper limit for gamma rays produced by CR electrons. To obtain an optimistic estimation of the CR electron density, we fit the observed gamma-ray spectrum assuming that all observed gamma rays result from CR electrons (Fig.2). Since the injection source is taken to be the same for CR protons and electrons, we expect the injection spectrum for both species to have the same spectral index. Considering spatial diffusion and losses, $Q_{0,p} = 2 \times 10^4$ MeV^{-3}s^{-1} is the best fit parameter for the electron injection spectrum. Since this injection spectrum is obtained using the gamma-ray flux produced by electrons above energy $E_e^* = 1.3$ GeV, the steady-state spectrum obtained from the injection is also valid only above E_e^*.

In the case of electrons also, the main contribution comes from below E_e^*. Extrapolating the same power-law to lower energies doesn't give a considerable increase in ionisation rate. We add a steeper power-law in the lower energies and obtain the observed ionisation rate for $\Delta = 5.0$ and $E_{e,min} \sim 100$ keV (Fig.3).

The minimum ionising energy of the electron, although higher than I, may also be too low. But, increasing $E_{e,min}$ poses the same problem as in the case of the protons. $\Delta = 5.0$ is also much steeper than expected spectra from current CR acceleration models. Moreover, the power needed in the CMZ is again approximately 10% of the total CR power in the Galaxy.

4. Conclusion

In this work, we question the assumption that CR particles are responsible for the increased ionisation rate in the CMZ. It is indeed possible to reach an ionisation rate above 10^{-14} s^{-1} with certain CR spectra. However, the suitable injection spectra have spectral indices ≥ 5.0 in low-energies while most "known" CR accelerators produce much harder spectra. We consider particles of energies down to keV, but this energy may be too low. Increasing the minimum energy also increases the steepness of the enhancement which is already extremely high. Either an unknown accelerator

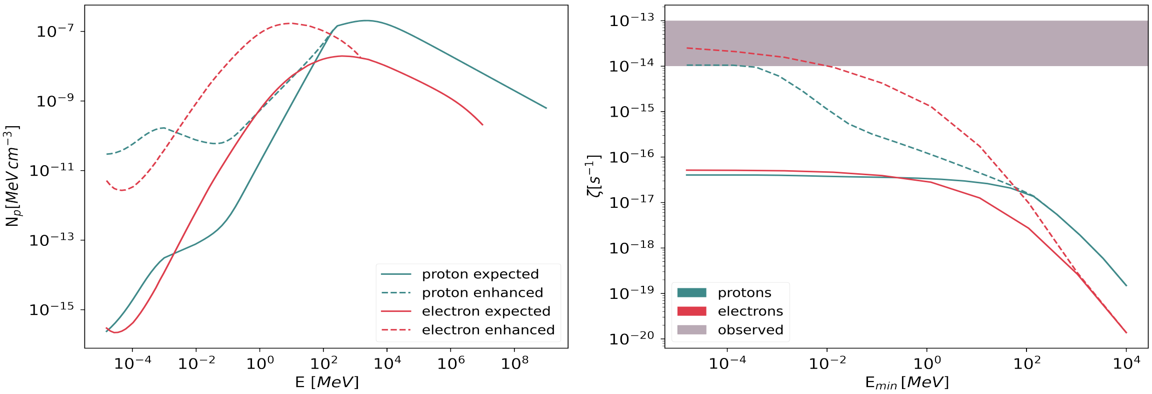

Figure 3: Left: Expected and enhanced spectra for CR protons and electrons. **Right:** Corresponding ionisation rates as a function of the minimum ionising energy.

or an unknown mechanism is needed to explain such steep spectra. Another issue is the huge cost of maintaining these spectra - 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 ~ 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 exclusive ionising agents.

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