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Cosmic-ray induced ionization rates and non-thermal emissions from nuclei of starburst galaxies

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Cosmic rays are believed to partially control the physical and chemical evolution of molecular clouds. In fact, the impact of cosmic rays on these star-forming regions could be approximately quantified via the cosmic-ray induced ionization rate $\zeta(\mathrm{H}_2)$. The aim of this work is to provide estimates for this quantity in the prototypical starburst nucleus of NGC 253 using non-thermal emissions (X-ray, GeV and TeV gamma-ray) from this objects. To this end, we employ a cosmic-ray transport model to fit data for non-thermal emissions and derive the cosmic-ray spectra in this system. We then adopt these cosmic-ray spectra to evaluate the ionization rates and find the values of $\zeta(\mathrm{H}_2)$ to be around 4×10^{-14} s^{-1} which is about 2 to 3 orders of magnitude higher than the typical values found in molecular clouds of the Milky Way. Such a high value of $\zeta(\mathrm{H}_2)$ is mostly due to the fact that these nuclei, with typical sizes of a few hundred parsecs, have relatively high rates of supernova explosions which are comparable or even higher than that of the entire Milky Way. Interestingly, the ionization rates have been inferred (using molecular line observations) to be around 10^{-13}, and in some extreme cases reaching 10^{-12} s^{-1}, for several clouds in the central molecular zone of NGC 253 which is higher than the values derived from our fit to the non-thermal emissions. We will discuss in more detail potential explanations for this discrepancy. The framework presented in this work, however, clearly illustrates the potential of non-thermal emissions as a tool to better quantify the impact of cosmic-ray in starburst environments and, in the future, might help us to gain more insights into the important role of cosmic rays as regulators of star-forming regions.

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1. Introduction

Starburst galaxies are galaxies with relatively high star formation rates typically about 10 to 100 times higher than that of the Milky Way [1]. The intense star-forming activities also result in high rates of supernova explosions and, as supernova remnants (SNRs) are commonly believed to be CR sources, starburst galaxies are expected to be filled with CRs. Of particular interest are the starburst nuclei (SBNi) which have sizes of about a few hundred parsecs but have the rates of supernova explosions comparable to or even higher than that of the entire Milky Way. It is for this reason that SBNi are considered ideal laboratories to study CR impact on star-forming regions.

It has long been suggested that CRs can play an essential role in setting the chemistry and even dynamics of star-forming regions [2]. This is because these particles could penetrate deep inside dense molecular clouds where X-rays and UV photons are shielded to ionize the interior of these objects. In other words, CRs control the ionization rate which is a key parameter in regulating the abundances of different chemical species in molecular clouds. More important, the ionization rate also determines the coupling between gas and magnetic fields which is of critical importance for the process of star formation. Thus, the impact of CRs on star-forming regions might be approximately quantified using the ionization rate $\zeta(\mathrm{H}_2)$.

Here, we will discuss a framework to estimate the ionization rate in SBNi which relies on non-thermal emissions from these objects. Many SBNi are actually bright gamma-ray sources both in the GeV and TeV energy range and some of them are also detected with X-ray telescopes [3]. The starburst galaxy NGC 253, for example, has been observed by both Fermi-LAT and HESS revealing its gamma-ray spectrum extending from a few hundred MeVs to about 10 TeV [4]. The gamma-ray emissions are likely to be from the decay of neutral pions produced mostly in interactions between CR protons and interstellar gas in the nucleus of NGC 253 [5]. This means that the gamma-ray spectrum could be employed to extract the CR proton spectrum within this SBN. In fact, NGC 253 has been investigated also with Chandra and NuSTAR X-ray telescopes but it is rather complex to identify whether these X-ray emissions are induced by CR electrons or they actually come from several X-ray binaries embedded in this starburst galaxy [6]. Nevertheless, the X-ray spectrum can be used as a upper limit to constrain the CR electron spectrum. The combination of these non-thermal emissions from X-ray to gamma-ray together provide a powerful tool to study CRs in starburst galaxies and, ultimately, allow us to quantify the impact of these particles in the star-forming activities of these systems.

The proceeding will be structured as follows. In Section 2, we will introduce the model to describe CR transport in SBNi. The model essentially provides the CR spectra which can be used to model different radiative processes and also evaluate the ionization rates as discussed in Section . We then use this model to fit the non-thermal emissions from the nucleus of NGC 253 to derive the CR spectra in this system. The spectra are then employed to give estimates for the ionization rate in this system which is smaller than the values recently inferred by [7] using molecular line observations (see Section 3.3). We give also a brief discussion in Section 4 on the implications of this discrepancy in terms of potential additional MeV CR sources in SBNi.

2. Cosmic-ray transport in starburst nuclei

We will adopt the one-zone model as presented in Ref. [5] to describe CR transport in SBNi. In this model, the differential number density $f_i(E)$ for CRs of species i = p (protons) or i = e (electrons) with kinetic energy E can be obtained by solving the following CR transport equation

$$\frac{f_i(E)}{\tau_{\rm adv}(E)} + \frac{f_i(E)}{\tau_{{\rm diff},i}(E)} - \frac{\partial}{\partial E}\left[b_i(E) f_i(E)\right] = Q_i(E). \tag{1}$$

where $Q(E)$ is the injection spectrum of CRs (either primary CRs accelerated SNR shocks or secondary and tertiary CRs produced in interactions of primary CRs with the ISM of SBNi), $b_i(E)$ is the energy loss rate due to interactions of CRs with SBNi's materials (see [8] for all relevant energy loss processes), $\tau_{\rm adv}$ and $\tau_{{\rm diff},i}(E)$ are respectively timescales for the escape of CRs from the SBNi due to advection and diffusion. We can estimate the advection timescale simply as $\tau_{\rm adv} = R/u_w$ where R is the radius of the SBNi and u_w is the speed of galactic winds in SBNi. The diffusion timescale can be approximated as $\tau_{{\rm diff},i}(E)^2/D_i(E)$ where D_i is the diffusion coefficient of CRs in SBNi. We will assume magnetic turbulence within SBNi following a Kolmogorov power spectrum as in Model A from Ref. [5] such that the diffusion coefficient is of the following form $D_i(E) = \frac{L_0 v_i}{2\eta_B}\left(r_{L,i}(E)/L_0\right)^{1/3}$ where L_0 = 1 pc is the injection scale of turbulence, $\eta_B = \delta B^2/B^2 = 1$ is the ratio between the variance of turbulent magnetic fields δB^2 and the ordered field strength squared B^2, v_i is the speed of CRs of species i with kinetic energy E, and $r_{L,i}(E)$ is the Larmor radius of CRs of species i with kinetic energy E.

The injection spectrum for CR protons can be modelled as a power law in momentum p

$$Q_{\rm p}(E) = Q_{\rm SNR,p}(E) = \frac{\mathcal{R}_{\rm SNR}\xi_{\rm CR,p}E_{\rm SNR}}{V\Lambda m_{\rm p}^2 c^3 v_{\rm p}}\left(\frac{p}{m_{\rm p}c}\right)^{2-\alpha}\exp\left(-\frac{p}{p_{\rm max,p}}\right), \tag{2}$$

where $\mathcal{R}_{\rm SNR}$ is the rate of supernova explosions within the SBN, $\xi_{\rm CR,p}$ is the fraction of supernova explosion kinetic energy converted into CR kinetic energy, $E_{\rm SNR} \simeq 10^{51}$ erg is the typical kinetic energy of supernova explosions, $p_{\rm max,p} \simeq 10^{17}$ eV/c is the cut-off momentum for CR protons accelerated from SNRs, $m_{\rm p}$ is proton mass, c is the speed of light, $V = 4\pi R^3/3$ is the volume of the SBNi, and $\Lambda = \int_{x_{\rm min}}^{\infty} x^{2-\alpha}\exp\left(-\frac{x}{x_{\rm max}}\right)\left(\sqrt{x^2+1}-1\right){\rm d}x$.

For CR electrons, the injection spectrum has three contributions $Q_{\rm e}(E) = Q_{\rm SNR,e}(E) + Q_{\rm sec}(E) + Q_{\rm ter}(E)$ where the terms are respectively for primary, secondary and tertiary CR electrons. The injection of primary CR electrons from SNRs can be described as $Q_{\rm SNR,e}(E) \sim \xi_{\rm CR,e}p^{2-\alpha}\exp(-p/p_{\rm max,e})$ with $\xi_{\rm CR,e} = 0.01$ and $p_{\rm max,e} \simeq 10^{13}$ eV/c. The injection spectrum of secondary electrons can be described following the approach presented in Ref. [9]

$$Q_{\rm sec}(E) = 2\int_E^{\infty}\frac{c n_{\rm ISM}}{K_\pi}\sigma_{\rm pp}\left(\frac{E_\pi}{K_\pi}\right) f_{\rm p}\left(\frac{E_\pi}{K_\pi}\right)\tilde{f}_e\left(\frac{E}{E_\pi}\right)\frac{{\rm d}E_\pi}{E_\pi}, \tag{3}$$

where $n_{\rm ISM}$ is the density of the ISM in SBNi, $K_\pi \simeq 0.17$ is the fraction of kinetic energy transferred from the parent proton to the single pion, $\sigma_{\rm pp}(E)$ is the total inelastic cross-section for interactions between CR protons with kinetic energy E and protons in the ISM of SBNi [10], $f_{\rm p}(E)$ is the differential number density of CR protons with kinetic energy E, and $\tilde{f}_{\rm e}(E/E_\pi)$ is defined as in [9]. As for tertiary electrons, the injection spectrum is

$$Q_{\rm ter}(E) = \frac{c}{R} f_\gamma(E_\gamma = E)\left[1 - \exp\left(-\tau_{\gamma\gamma}(E_\gamma = E)\right)\right], \tag{4}$$

where $f_\gamma(E)$ is the differential number density of gamma rays induced by CRs and $\tau_{\gamma\gamma}(E)$ is the opacity of gamma rays due to interactions with low-energy photons in the ISM of SBNi which could be estimated as follows

$$f_\gamma(E_\gamma) \simeq \frac{R}{c}\int_0^\infty \mathrm{d}E_\mathrm{p} f_\mathrm{p}(E_\mathrm{p})\epsilon_\mathrm{PPI}(E_\mathrm{p},E_\gamma), \tag{5}$$

$$\tau_{\gamma\gamma}(E_\gamma) \simeq \sum_\mathrm{rad}\frac{U_\mathrm{rad}}{k_B T_\mathrm{rad}}\sigma_{\gamma\gamma}(E_\gamma, k_B T_\mathrm{rad})R. \tag{6}$$

Here, we have introduced the volume emissivities for gamma-ray production by the decay of neutral pions created from proton-proton interactions ϵ_PPI. This process will be discussed in more detail in the next section. In principle, the injection spectrum of tertiary electrons should depend also on other radiative processes such as bremsstrahlung radiation or inverse Compton scattering induced by CR electrons themselves. However, the observed gamma-ray spectrum of SBNi is most likely dominated by the hadronic gamma-ray as we shall see later and, thus, it is sufficient to consider only tertiary electrons from hadronic gamma rays. As for the opacity of gamma rays in SBNi, we have introduced also the gamma-gamma interaction cross-section $\sigma_{\gamma\gamma}(E, E_\mathrm{ph})$ [11] and note that the sum in Eq. 6 is performed over different components of the interstellar radiation fields including far-infrared (FIR), mid-infrared (MIR), near-infrared (NIR), and optical (OPT).

3. Non-thermal emissions and ionization rates in starburst nuclei

3.1 Cosmic-ray induced gamma rays and X-rays

In this section, we will discuss briefly the most relevant processes for non-thermal emissions induced by CRs including gamma rays from the decay of π_0 in proton-proton interactions, bremsstrahlung radiation, inverse Compton scattering, and synchrotron radiation. In fact, the most dominant radiative mechanism for GeV and TeV gamma rays from the SBNi of interest is perhaps π_0 decay whose volume emissivity can be described as

$$\epsilon_\mathrm{PPI}(E_\mathrm{p},E_\gamma) = n_\mathrm{ISM} v_\mathrm{p} \varepsilon_\mathrm{n}(E_\mathrm{p})\frac{\mathrm{d}\sigma_\mathrm{pp}(E_\mathrm{p},E_\gamma)}{\mathrm{d}E_\gamma}, \tag{7}$$

where $\mathrm{d}\sigma_\mathrm{pp}/\mathrm{d}E_\gamma$ is the differential cross-section for proton-proton interactions and $\varepsilon_\mathrm{n}(E_\mathrm{p})$ is the nuclear enhancement factor (to correct for gamma rays induced by CR nuclei) from [10]. Note that such a differential cross-section will be non-zero only for CR protons with kinetic energy satisfying $E \leq E_\gamma + m_\pi^2 c^4/(4E_\gamma)$.

Cosmic-ray electrons can also induce gamma rays via bremsstrahlung radiation where photons are produced in interactions between CR electrons and interstellar gas. Another important process is inverse Compton scattering where low-energy photons in the interstellar radiation fields are boosted to much high-energy after being scattered by CR electrons. In addition, since SBNi have also relatively strong magnetic fields, X-rays or MeV gamma rays can also be induced via synchrotron radiation. We refer interested readers to Ref. [5] for more details on specific formulae for the volume emissivity of all these radiative processes. Given properties of the interstellar medium in SBNi, the differential number density of high-energy photons $f_\gamma(E_\gamma)$ can be estimated as in Eq. 5 and the expected flux of gamma rays and X-rays from these SBNi is then given as $\phi_\gamma(E_\gamma) = f_\gamma(E_\gamma)c\left(R/d_\mathrm{gal}\right)^2/3$, where d_gal is the distance between the SBN and the Milky Way.

3.2 Cosmic-ray induced ionization rates

Once the CR spectra in SBNi are determined by fitting the transport model to data for non-thermal emissions, the ionization rate can be estimated. In fact, predictions of this quantity require also a model to describe the propagation of CRs into molecular clouds which could be either *ballistic* (gyrating along magnetic field lines, [12]) or *diffusive* (executing random walks along magnetic field lines, [13–15]) depending on the geometry of magnetic fields around these clouds [16]. In SBNi, high supernova rates might lead to very turbulent magnetic fields with rather short correlation length, i.e. comparable to sizes of molecular clouds in these systems. Thus, we will assume the propagation into clouds to follow the ballistic model. This model essentially gives the average CR spectra in a cloud $f_{i,cl}(E)$ given the interstellar spectra $f_i(E)$ depends only on the total column density of H_2 in the cloud $N(H_2)$.

The H_2 ionization rate induced by CR protons and electrons could be obtained as in [12, 14]

$$\zeta_i(H_2) \quad = \quad \int_{I(H_2)}^{\infty} f_{i,cl}(E)\, v_i\, [1+\phi_i(E)]\, \sigma^i_{\rm ion}(E)\, {\rm d}E \tag{8}$$

where $\sigma^i_{\rm ion}$ is the ionization cross-section of CR species i, $\phi_i(E)$ are the average secondary ionization per primary ionization, and $I(H_2) = 15.603$ eV is the ionization potential of H_2. The total CR-induced ionization rate is then estimated as $\zeta(H_2) \simeq 1.5\zeta_{\rm p}(H_2) + \zeta_{\rm e}(H_2)$.

3.3 Implications for the starburst nucleus of NGC 253

We will now apply the framework introduced above to the nucleus of the starburst galaxy NGC 253 which is a spiral galaxy located at a distance of $d_{\rm gal} \simeq 3.8$ Mpc from the Milky Way [17]. This starburst galaxy is believed to have a higher star formation rate (SFR) than the Milky Way with about 70% of the star-forming activities occurring in the starburst nucleus region [18]. Thus, the NGC 253 starburst nucleus, which is of size $R \simeq 100$ pc, also has a relatively high supernova rate $\mathcal{R}_{\rm SNR} \simeq 0.03$ yr^{-1} comparable to that of the entire Milky Way [19].

This system is interesting because the ionization rates in the central molecular zone of the starburst galaxy NGC 253 have been recently measured using molecular line observations [7]. This study reveals relatively high values of ionization rates for several clouds in the nucleus of NGC 253 reaching about 10^{-13} to 10^{-12} s^{-1} which are about 2 to 3 orders of magnitude higher than typical values observed in Galactic molecular clouds. These measurements are, however, *indirect* as they have to rely on Bayesian analysis of chemical and radiative transfer models in order to infer the value of the ionization rates. This also means that the resulting values of $\zeta(H_2)$ might be very sensitive to the exact physical and chemical properties within the clouds in consideration. These properties could be rather sophisticated to determine especially in starburst environments where the interstellar medium might be affected by many competing feedback processes due to intense star-forming activities (cosmic-ray induced ionization, mechanical heating due to shocks and turbulence from supernova explosions, radiative heating induced by massive stars, see e.g. [20]).

Since the SBN of NGC 253 is also observed by X-ray and gamma-ray telescopes, we could also provide estimates for ionization rates in this system using these non-thermal emissions. We first fit the GeV and TeV gamma-ray spectrum observed Fermi-LAT and H.E.S.S. telescopes [4] to derive the CR spectra within the SBN of NGC 253 (see Fig. 1). We ensure also that the expected

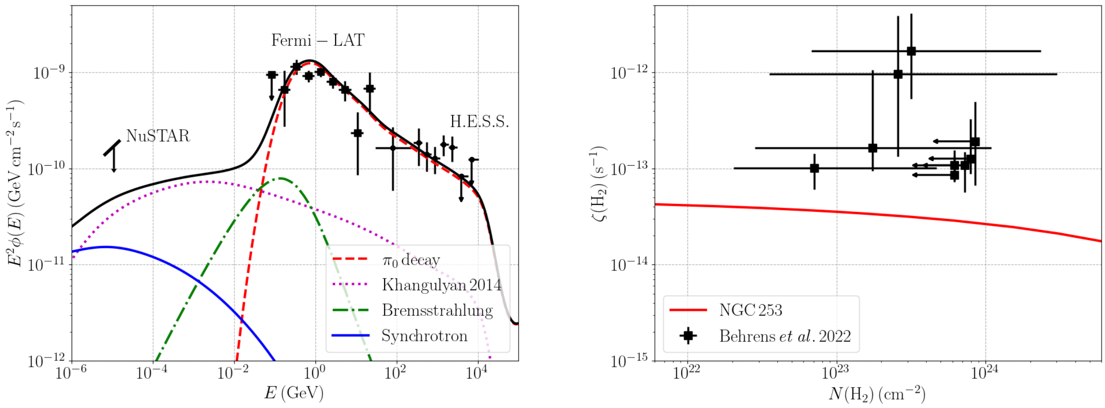

Figure 1: Left panel: Non-thermal emissions from the SBN of NGC 253. The total flux (black line) is fitted to gamma-ray data from Fermi-LAT and H.E.S.S. [4] and upper limits from NuSTAR [6]. Right panel: Ionization rate expected in the SBN of NGC 253 (red line) and inferred values for a few molecular clouds in the central region of NGC 253 from molecular line observations [7].

X-ray emissions are compatible with upper limits set by NuSTAR [6]. We adopt most parameters as in Ref. [5] except of the size of the SBN which we adopt $R \simeq 100$ pc for a better fit of gamma-ray spectrum using the updated pion production cross sections.

The CR spectra are then used to compute ionization rates for clouds of different column densities as presented in the right panel of Fig. 1. Interestingly, the ionization rate could reach about $\zeta(\mathrm{H_2}) \simeq 4 \times 10^{-14}$ s^{-1} for clouds with $N(\mathrm{H_2}) = 10^{23}$ cm^{-3}. It is clear the ionization rate in this work is rather close to (being about 2 or 3 times below) the values inferred for most clouds investigated in Ref. [7]. There are two clouds where the inferred ionization rates are particularly high about 100 times higher than the value predicted in this work. These differences might be due to the existence of MeV CR sources and we will elaborate more on this point in Section 4.

4. Discussions and Conclusions

We have introduced a general framework to predict ionization rates in SBNi which relies on non-thermal emissions from these objects. As an illustration, we apply this framework to the case of NGC 253. We first fit X-ray and gamma-ray spectrum from the nucleus of this system to derive the CR spectra. These spectra are then implemented in a transport model to describe the penetration of CRs into dense molecular clouds which allow us to predict the ionization rate for clouds of different column densities.

The predicted ionization rate for the SBN of NGC 253 is about 4×10^{-14} for clouds with $N(\mathrm{H_2}) \simeq 10^{23}$ cm^{-2} which is about found to be about 2 to 3 times lower than the values inferred for most clouds analyzed in Ref. [7]. However, there are two clouds where the inferred ionization rates are 100 times higher than predicted with our framework. Such a discrepancy might be due to local sources of MeV CRs. It is clear from the left panel of Fig. 1 that the non-thermal emissions of these SBNi in the GeV and TeV energy, where data are most constraining, are contributed mostly from the decay of π_0 created in proton-proton interactions. The production of π_0, however, has a threshold $E_{\rm th} \simeq 280$ MeV meaning that these gamma-ray data could not probe CR protons with $E \lesssim E_{\rm th}$. In other words, there might exist a class of sources accelerating mostly CRs in the energy range of around a few hundred MeVs, e.g. wind termination shocks of stars [21] or protostellar jets embedded within molecular clouds [22, 23], that contribute to the ionization rate in these systems but could not be observed with GeV and TeV gamma-ray telescopes. We note also that if these MeV sources exist in SBNi and they are sufficiently abundant, they might contribute to the gamma-ray emissions in the MeV energy range.

Further investigations might be required to improve our understanding on the values of the ionization rates. Nevertheless, the framework introduced in this work is sufficiently general to provide estimates for ionization rates in SBNi (only a factor 2 or 3 lower than values inferred with molecular line observations in most cases). This framework will be useful for advancing our understanding on the impact of CRs in starburst environments, especially in star-forming regions where the use of chemical and radiative transfer models might no longer be straightforward.

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