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Cosmic ray induced ionization of molecular clouds embedded in the wind blown bubbles of massive star clusters

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Young massive stellar clusters (YMSCs) are able to modify the circumstellar medium around them thanks to the feedback produced by the powerful winds of massive stars, which inflate low-density bubbles with sizes of tens to a hundred parsecs. As the entire cavity grows in time, the regular interstellar medium is swept away, and wind advection modulates the propagation of low-energy Galactic cosmic rays (CR), potentially preventing their penetration inside the bubble. In such a situation, dense molecular clouds positioned inside the wind-blown bubble can only be ionized by CRs self-produced by sources inside the YMSC (like stellar winds). Recently, YMSCs have been suggested to be powerful sources of CRs. Hence, in this presentation, we propose to use the ionization level of clouds close to YMSC to estimate the production efficiency of low energy CRs. We specialize our calculations to a model where CR acceleration occurs at the termination shock of stellar winds, investigating how the ionization rate induced by such freshly accelerated particles differs from the one expected by the average Galactic CR flux. Finally, we focus on the specific case of the Cygnus OB2 association. We show how the combination of gamma-ray observations and measurements of the ionization level of nearby molecular clouds represents a powerful tool to constrain the properties of the CR distribution in the cluster neighborhood.

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1. Introduction

Young massive stellar clusters (YMSCs), thanks to the feedback provided by the powerful winds launched by the OB-type stars, are able to shape the environment around them by creating large hot bubbles in the interstellar medium (ISM). The expansion of these cavities sweeps the ISM, generating dense shells that subsequently fragment, triggering the formation of new stars [5, 16]. The environment in which the wind bubbles expand and evolve is highly clumped, as it originates from the collapse of the parent giant molecular cloud. It is therefore natural to expect that some gas clumps, related to the parent giant molecular cloud or to the fragmenting shell, will end up being encompassed within the expanding hot bubble.

Cosmic rays (CRs) play a fundamental role in the process of star formation [11]. They regulate the gravitational collapse of a gas cloud by influencing the ionization degree of the cloud itself [15]. The environment of the wind blown bubble is characterized by a population of low-energy (< a few GeV) CRs different from the one found in the ISM. Due to the highly turbulent nature of the hot plasma in the bubble, particle diffusion is expected to be suppressed [9]. This, together with the expansion of the cavity, prevents the low-energy CRs in the ISM to penetrate the bubble. As a result, the population of particles within the hot cavity is solely sustained by the CRs accelerated in the YMSC. Depending on the properties of the accelerated particle spectrum, the type of diffusion coefficient in the bubble, and the cavity properties (such as magnetic field and particle density), the CR flux permeating the cloud can be enhanced or suppressed with respect to the CR flux in the unperturbed ISM. This leads to an increase or decrease of the cloud ionization rate, which ultimately can affect the star formation process.

Since the ionization degree of the clump is only provided by the CR population accelerated in the cluster, the measurement of the ionization rate, paired with the information from γ-ray observations, also represents a unique probe to investigate the distribution of particles in the bubble, and hence the propagation properties in these environments.

In this work, we aim to study the CR induced ionization of molecular clumps or molecular clouds (MCs) encompassed within the bubble blown by the wind from YMSCs. We consider the case where particle acceleration occours at the collective cluster wind termination shock (TS). This scenario, along with a study of the propagation of particles is presented in [9]. In the first part of the work, we calculate the ionization rate for two mock MCs with average column density of 10^{22} cm^{-3} and 10^{23} cm^{-3}. In the second part of the paper, we compute the ionization rate considering the specific case of the MC DR21, located close to the Cygnus OB2 YMSC [13]. In this specific case, we consider the ionization rate induced by a population of CRs whose characteristics are fixed in order to reproduce the observed γ-ray emission at high and very high energy [7]. Comparison with measures of the ionization rate are also provided.

The paper is structured as follows: in §2, we first describe the particle distribution in the wind blown bubble and, afterward (§3), we present the employed model used to describe CR propagation within a molecular cloud. In §4, we describe the computation of the ionization rate in molecular clumps. In §5, we focus on the specific case of DR21, and we compare the expected ionization rate with estimations available from the literature. Finally, in §6 we report the conclusion and future prospects of this work.

2. Cosmic ray production in YMSCs

In YMSC, when the average distance between stars is smaller than the TS of individual stellar winds, the winds from massive stars may merge to form a collective cluster wind. This scenario is expected to be common due to primordial mass segregation, which is typically observed in young clusters (see [7] and references therein). As the wind material undergoes shock and heating, it expands adiabatically within the interstellar medium (ISM), resulting in the formation of large bubble-like structures whose dynamics is similar to that observed around isolated massive stars [17]. A model for particle acceleration in these systems has been presented by [9]. This model can be summarized as follows: particles are accelerated at the TS of the collective cluster wind through the process of diffusive shock acceleration, and subsequently they escape from the acceleration site, experiencing a combination of advection and diffusion within the hot bubble until they reach the bubble boundary. At that point, cosmic rays (CRs) are able to freely escape into the ISM.

Given the highly turbulent nature of the hot bubble, particle diffusion is suppressed and propagation below a few GeV is entirely ruled by advection. As a result, low-energy particles from the ISM are not able to penetrate inside the bubble boundary. As CRs are continuously accelerated at the TS and advected away, the spectrum at any position in the bubble is the same as that at the injection, which is [7, 9]:

$$f_{TS}(p) = \mathcal{A}(\epsilon_{CR}, L_w, \dot{M}) \left(\frac{p}{m_p c}\right)^{-s} \left[1 + a_1 \left(\frac{p}{p_{max}}\right)^{a_2}\right] e^{-a_3 (p/p_{max})^{a_4}} , \tag{1}$$

where s is the spectral slope of injected particles, the parameters a_1, a_2, a_3 and a_4 depend on the spectral behavior of the diffusion coefficient, which is ultimately related to the type of magneto-hydrodynamic turbulence spectrum. The coefficients are listed in [7] (Tab. 1.1) for Kolmogorov, Kraichnan and Bohm like diffusion. The parameter $\mathcal{A}$ is a normalization factor which depends on the cluster mass loss rate, wind power, and the efficiency of CR production (ϵ_{CR}) (see [7], Eq. 1.75). The parameter $p_{max} = E_{max}/c$ is the maximum momentum at which particles can be accelerated, which can be found by the condition $D_1(E_{max})/v_w = R_{TS}$, where D_1 is the diffusion coefficient in the cold cluster wind, $v_w = (2L_w/\dot{M})^{1/2}$ is the collective cluster wind speed and $R_{TS} = 0.791 \dot{M}^{1/2} v_w^{1/2} L_w^{-1/5} \rho_0^{-3/10} t^{2/5}$ is the size of the TS [17]. The factors t and $\rho_0 = n_0 m_p$ (where m_p is the mass of the proton) are respectively the age of the system and the density in which the bubble expands.

3. CR propagation in MCs

A MC located inside the cluster bubble will be crossed by CR accelerated at the termination shock. The spectrum inside the MC will be modified by energy losses, however, here we assume that the MC is much smaller than the bubble such that the average CR spectrum outside of the MC is not significantly affected by losses. We describe the CR spectrum using the model developed by [8] where the propagation is simplified by solving the a 1D transport equation that account for losses, self-generation of waves as well as they damping. The CR spectrum result from the balance between the advective flux entering the cloud, given by $2 v_A f_{\rm TS}$ (v_A being the Alfvén speed in the hot bubble), and the flux due to energy losses. The result gives [8]:

$$f_{\rm MC}(p) \approx \begin{cases} f_{\rm TS}(p) & \text{for } p \geq p_{\rm br} \\ f_{\rm TS}(p_{\rm br}) \left(\frac{p}{p_{\rm br}}\right)^{-0.42} \left\{1 - \frac{1}{s-3} \frac{v_A \tau_{\rm loss}(p)}{L_{\rm MC}/2} \left(\frac{p}{p_{\rm br}}\right)^{-2.58} \left[1 - \left(\frac{p}{p_{\rm br}}\right)^{3-s}\right]\right\} & \text{for } p < p_{\rm br} \,. \end{cases} \quad (2)$$

where $L_{\rm MC}$ is the characteristic size of the MC and $\tau_{\rm loss}$ is the ionization loss time scale in a MC with medium density $n_{\rm MC}$, which reads:

$$\tau_{\rm loss}(p) = 1.46 \times 10^5 \left(\frac{p}{0.1\, m_p c}\right)^{2.58} \left(\frac{n_{\rm MC}}{1\ {\rm cm}^{-3}}\right)^{-1} \ {\rm yr}. \quad (3)$$

One can see from Eq. (2) that the spectrum is modified only below $p_{\rm br}$, which represent the critical momentum where propagation time is equal to the loss time. The corresponding characteristic energy is

$$E_{\rm br} \simeq 70 \left(\frac{v_A}{100\ {\rm km\, s^{-1}}}\right)^{-0.78} \left(\frac{N_{\rm MC}}{3 \times 10^{21}\ {\rm cm}^{-2}}\right)^{0.78} \ {\rm MeV} \quad (4)$$

where $N_{\rm MC} = n_{\rm MC} L_{\rm MC}$ is the cloud columd density.

4. Ionization of MC embedded within the wind blown bubble of a YMSC

As the wind-blown bubble develops around a newly born YMSC, it may happen that a MC, generated by the collapse of the parental giant molecular cloud or by the fragmentation of the swept up shell of ISM, is embedded within the hot bubble plasma. Let us consider two different cases of a compact dense clump, with size L_c = 1 pc and column density $N_{MC} = 10^{23}$ cm^{-2} and $N_{MC} = 10^{22}$ cm^{-2} respectively. We assume the cluster younger than $t \sim 3$ Myr, so that no supernova should have exploded within it yet [4]. We furthermore fix the wind luminosity and mass loss rate of the YMSC to $L_w = 3 \times 10^{36}$ erg s^{-1} and $\dot{M} = 10^{-6}$ M$_\odot$ yr^{-1} respectively, which are average values expected for YMSC [7]. We also assume that 10% of the wind luminosity is spent to accelerate particles ($\epsilon_{CR} = 0.1$). Two additional parameters required are the magnetic field and density in the bubble, which are affected by large uncertainties. The shell fragmentation and turbulent mixing with the external interstellar medium can lead to a wide possible range of density values. The magnetic field in the bubble likely originates from the turbulent dissipation of the shocked cluster wind. Whether the conversion of wind power into a turbulent magnetic field arises with a certain radial profile or is constant along the bubble is totally unknown. We hence consider a wide range of possible densities and magnetic field intensities, more precisely $n_2 = 10^{-3} - 1$ cm^{-3} and $B_2 = 1 - 50$ μG. We finally assume that particle diffusion in the bubble is mediated by a Kraichnan like diffusion coefficient (see [7], Eq. 1.79), and that the turbulence injection scale is equal to 1 pc, which is the typical dimension of a YMSC.

We compute the ionization rate of molecular gas (ζ_{H_2}) using the recipe provided by [10]:

$$\zeta_{H2} = \int_{I(H_2)}^{E_{max}} c f_{MC}(E)[1 + \phi(E)]\sigma_{\rm ion}(E) dE \quad (5)$$

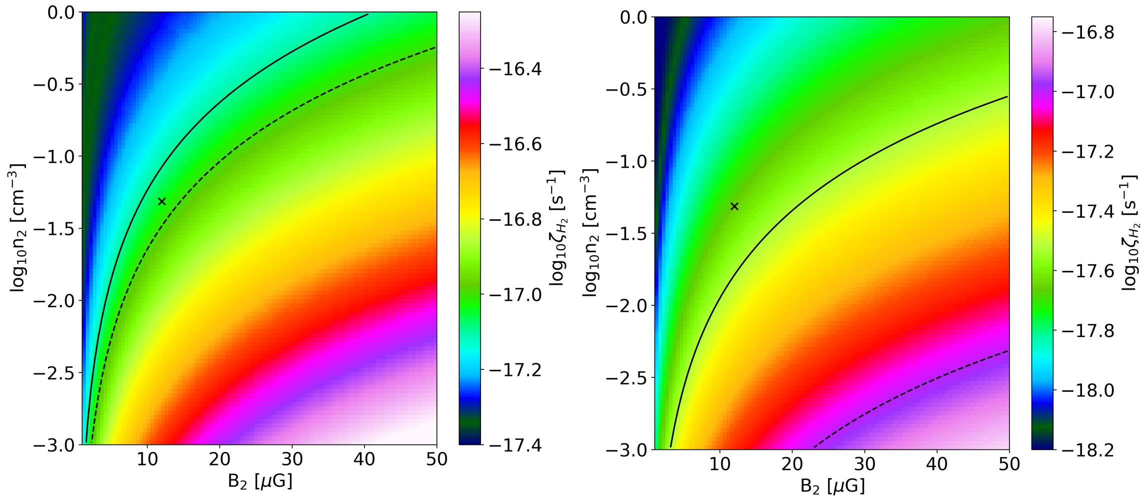

Figure 1: Left panel: Ionization rate induced by primary protons as a function of bubble density and magnetic field for a clump with $N_{MC} = 10^{22}$ cm^{-2}. The dashed line indicates the standard Spitzer value [15], while the cross marks our results obtained for values of B_2 and n_2 consistent with the YMSC properties (see text). The solid line indicates the ioniazation rate as estimated by [12]. Right panel: same as left panel but for a MC with $N_{MC} = 10^{23}$ cm^{-2}

where $I(H_2) = 15.603$ eV is the ionization potential of H_2, and σ^{ion} is the cross section for direct ionization (see [10] and references therein). The quantity $\phi(E)$ is a correction factor accounting for the ionization induced by a population of secondary electrons created by direct ionization, and can be calculated as:

$$\phi(E) = \frac{1}{\sigma_{\text{ion}}(E)} \int_{I(H_2)}^{E_{max}} \mathcal{P}(E, E'_e)\sigma_e^{\text{ion}}(E'_e)dE'_e \tag{6}$$

with the term $\mathcal{P}(E, E'_e)$ describing the probability that a secondary electron with energy E'_e is created during a primary ionization by a proton with energy E [10].

Fig. 1 show the ionization rate obtained as a function of the magnetic field and density in the hot bubble for the MC with $N_{MC} = 10^{22}$ cm^{-2} (left panel) and $N_{MC} = 10^{23}$ cm^{-2} (right panel). Noticeably, the value can significantly differ from the Spitzer value ($\zeta_{Spitzer} \approx 10^{-17}$ s^{-1}) [15], which is the ionization rate expected from the low-energy population of CR in the ISM. More precisely, for high (low) magnetic fields and low (high) density the ionization rate is higher (lower), which implies a higher (lower) ionization degree of the cloud which could lead to a negative (positive) feedback for star formation. For the sake of completeness, we recall that the Spitzer value should be considered only as a reference value, as it is calculated without accounting for the physics of CR propagation within the cloud. In [12] a better estimation for the ionization rate using a refined version of the approach used by [8] is provided.

In Fig. 1 we also show the ionization rate obtained by fixing the magnetic field intensity and density in the bubble to values directly linked to the properties of the YMSC. More precisely, the magnetic field intensity is obtained assuming that 10% of the wind luminosity of the cluster wind is dissipated at any position in the bubble into turbulent magnetic field [7]. The density is calculated considering the mass evaporation rate from the cold swept up shell of ISM material due to heat conduction (see [7], Eq. 4.9).

5. The case of DR21, a molecular cloud close to Cygnus OB2

Cygnus OB2 is one of the most massive stellar clusters in the Milky Way, and is located towards the Cygnus-X star forming complex. The presence of plenty of MCs in direct interaction with the cluster [14] makes the system the perfect testing ground to investigate how YMSC affect the ionization rate in their neighborhood. Among the several MCs, DR21 is known to be in close proximity [13], and possibly embedded, in the wind blown bubble generated by Cygnus OB2.

The large diffuse γ-ray radiation detected in coincidence with Cygnus OB2 [1–3], supplies crucial hints on the CR distribution in the neighborhood of the cluster. We calculate the ionization rate of DR21 using the CR distributions provided by [7], which are derived by fitting the model developed by [9] (assuming a pure hadronic scenario) to the observed γ-ray emission. Among the CR distributions provided, we consider the one derived using a Kraichnan and Bohm-like diffusion coefficient. We also employ the same parameters for Cygnus OB2 as in [7], where the mass loss rate ($\dot{M}_{\rm CygOB2} = 10^{-4}$ M$_\odot$ yr^{-1}) is fixed to the value inferred from the cluster stellar population, while the wind luminosity (L_w), spectral slope of injected particles (s) and efficiency of CR acceleration (ϵ_{CR}) are fitted parameters of the model (see [7] Tab 2.1).

The ionization rate for DR21 is calculated using Eq. 5. We found a ionization rates of $\zeta_{H_2} \approx 1.88 \times 10^{-18}$ s^{-1} and $\zeta_{H_2} \approx 1.08 \times 10^{-18}$ s^{-1} for the Kraichnan and Bohm cases respectively. As shown in Fig. 2, these values are in agreement with the ionization rate inferred by the observation of HCO$^+$ [6], which is lower than the ionization rate we would expect from the Galactic CR sea [10].

Finally, it is worth highlighting that in the study conducted by [7], the derivation of the CR distribution through the fitting of the γ-ray emission is carried out using a target density of approximately 8 cm^{-3}. This density value is obtained from observations of neutral hydrogen and ^{12}CO and is utilized as both the density outside (n_0) and inside (n_2) the bubble. However, it should be noted that while the density within the bubble remains largely unknown, this value is likely too high. In terms of the γ-ray spectrum, the efficiency (ϵ_{CR}) and the density in bubble are totally degenerate parameters. This means that the same γ-ray spectrum can be re-obtained by keeping constant the product $n_2\epsilon_{CR}$ while varying both. Following this reasoning, we additionally consider the case where the CR efficiency is fixed to $\epsilon_{CR} = 0.1$, and the bubble density is changed accordingly. All other parameters are fixed to their previous best-fit values. The resulting ionization rates are $\zeta_{H_2} \approx 5.98 \times 10^{-17}$ s^{-1} and $\zeta_{H_2} \approx 6.27 \times 10^{-18}$ s^{-1} for the Kraichnan and Bohm cases respectively. Interestingly, only the Bohm case is in good agreement with the measured ionization rate. The Kraichnan case returns a ionization rate of more than one order of magnitude higher than the measured one. This is a remarkable result, showing that the measurement of the ionization rate of closeby MCs, combined with γ-ray observations, can be used to constrain (and in some cases even exclude) the models of CR diffusion in YMSCs.

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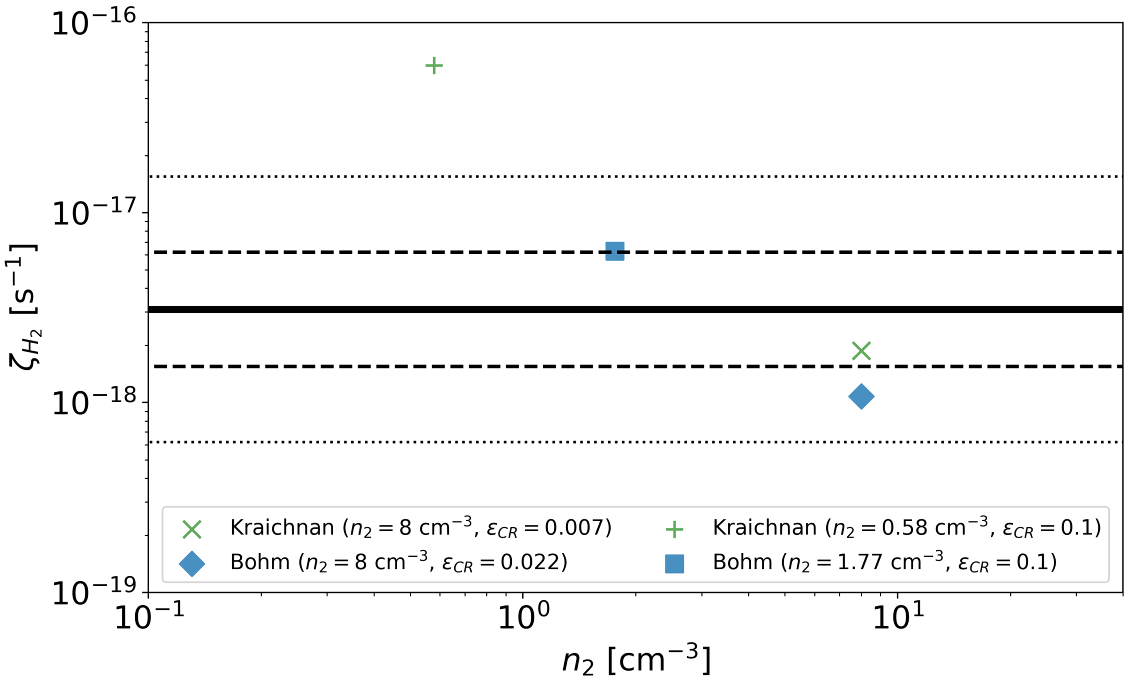

Figure 2: Ionization rates estimated for DR21. Cross and X points report the ionization rates for the Kraichnan case for fixed n_2 (derived by [7]) and ϵ_{CR} respectively. The same holds for the Bohm scenario, denoted by square and diamond markers respectively. The solid line indicates the ionization rate measured by [6]. Dashed and dotted lines report the uncertainty bars for a factor of 2 and 5 respectively.

6. Conclusions and future prospects

CRs play a crucial role in the process of star formation, which frequently occurs in large regions of a galaxy that are rich in clusters of young massive stars. The winds from the massive stars in the cluster inflate large hot cavities which end up modulating the spectrum of low-energy CRs. The study of the ionization rate in MCs close to a YMSC is a relevant diagnostic to understand the physics of CRs in these objects. First, understanding how YMSCs can affect the population of CRs in their neighborhood is a crucial aspect to better comprehend the process of star formation. Eventually, the enhancement (the suppression) of the content of CRs within the wind-blown bubble can induce negative (positive) feedback for star formation. Secondly, the measurement of the ionization rate, coupled with γ-ray observations, provides a unique method to constrain particle propagation in the vicinity of a stellar cluster, returning in addition valuable information on the CR spectrum at low energy.

The work presented in this paper is split in two parts. In the first one, we estimated the ionization rate for a MC in close proximity of a typical Galactic YMSC, considering two possible column densities for the MC: $N_{MC} = 10^{23}$ cm^{-2} and $N_{MC} = 10^{22}$ cm^{-2}. We found that the ionization rate can significantly differ from Spitzer value depending on the magnetic field and density in the hot wind blown bubble.

In the second part of the work, we focused on the specific case of the molecular cloud DR21, which is located close to the YMSC Cygnus OB2. We calculated the ionization rate for DR21 considering CR distributions whose properties are derived by fitting the observed diffuse γ-ray emission detected in coincidence with Cygnus OB2. We found the ionization rate consistent with the value inferred from HCO^+ observations. When using more realistic density in the bubble, we found that Bohm-like diffusion for particle propagation within the bubble is preferred.

The presented work is still in an early stage of development and multiple improvements are possible, such as the inclusion of the contribution to the ionization rate from primary electrons, and a quantitative estimate of the effect on the local star formation. Finally, the extension of this study to other MCs in addition to DR21 is foreseen.

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