Constraining cosmic ray acceleration in young star clusters using multi-wavelength observations

Siddhartha Gupta$^{1,2}$ *, Biman B. Nath$^{1}$, Prateek Sharma$^{2}$

$^{1}$Raman Research Institute, Sadashiva Nagar, Bangalore 560080, India
$^{2}$Joint Astronomy Programme and Department of Physics, Indian Institute of Science, Bangalore 560012, India

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ABSTRACT

We use 1D and 3D two-fluid cosmic ray (CR) hydrodynamic simulations to investigate the role of CRs in the vicinity of a compact young star cluster. We model a self-gravitating cloud (density profile $\rho \propto r^{-1}$), include important thermal and non-thermal processes, and explore two different CR injection scenarios. We show that if internal shocks in the wind-driving region are the main site for CR acceleration, then the resulting $\gamma$-ray luminosity ($L_{\gamma}$) can reach $\approx 5\%$ of the mechanical luminosity ($L_w$), independent of the fraction of wind energy ($\sim 1-20\%$) injected into CRs. In contrast, if the forward/reverse shock of a bubble is the injection site then $L_{\gamma}$ increases linearly with the CR injection fraction, as expected analytically. We find that the X-ray luminosity ($L_x$) in the forward/reverse shock injection scenario is $\gtrsim 10^{-3}L_w$, which is $\sim 10$ times larger than in the central wind-driving injection case. We predict the corresponding range of the synchrotron radio luminosity. We show how multi-wavelength observations can constrain the CR parameters. Comparing the predicted multi-wavelength luminosities with those of 30 Doradus we identify the reverse shock as the most probable CR injection site, and that thermal conduction is important. We do not find significant dynamical impact of CRs in our models.

Key words: hydrodynamics – cosmic rays – ISM : bubbles – galaxies: star clusters: general

1 INTRODUCTION

Star clusters are among the most fundamental objects in a galaxy. They are located in the core of dense molecular clouds and contain several thousand solar mass (for a review see Longmore et al. 2014). The stars energize the surrounding medium, leading to gas expulsion and the formation of interstellar bubbles (ISBs).

The theoretical modeling of ISBs serves as a standard scenario for the wind and ISM interaction (Weaver et al. 1977). Observations in X-rays, ultraviolet and infrared (e.g., Chu et al. 2003; Townsley et al. 2006; Lopez et al. 2014) have helped in our understanding of ISBs. Recent works have attempted to relax some of the assumptions in the standard scenario, for example, include the effect of different forms of pressure other than thermal pressure, or include the effect of spatial distribution of stars. It has been found that the dynamics of ISBs strongly depend on the clustering of stars and on the ambient density (e.g., Nath & Shchekinov 2013; Krause et al. 2013; Sharma et al. 2014; Kim & Ostriker 2015; Martinez, Faucher-Giguère & Quataert 2015; Yadav et al. 2017, Vasiliev, Shchekinov & Nath 2017). The effect of stellar radiation has also been studied (Harper-Clark & Murray 2009; Silich & Tenorio-Tagle 2013; Dale et al. 2013). It has been shown that radiation pressure can boost gas expulsion in the early phase ($\lesssim 1$ Myr) whereas the late time evolution is governed by the mechanical energy injection and photo-heating (Gupta et al. 2016). There is another promising driving mechanism, namely, the pressure due to relativistic particles such as cosmic rays (CRs), whose effects are yet to be understood in detail.

Star forming regions have been thought to be efficient sites for CR acceleration (Knödlseder 2013; Bykov 2014; Aharonian, Yang & de Oña Wilhelmi 2018). Several ISBs have
been identified as powerful sources of gamma-rays (hereafter, γ-rays) [The Fermi and H.E.S.S. collaboration]. Ackermann et al. (2011) found that the Cygnus OB association is quite bright in GeV range. Yang, de Oña Wilhelmi & Aharonian (2018) reported γ-ray emission in Westerlund 2. High energy photons have also been detected from the Large Magellanic Cloud (LMC). It has been reported that a massive star cluster, 30 Doradus, produces both GeV and TeV photons (Abdo et al. 2010, Abramowski et al. 2015). In a few cases, the γ-ray luminosity is ~ 1% of the wind mechanical power, and it is almost comparable to the X-ray luminosity (c.f. Table 1). Furthermore, Hughes et al. (2007) concluded that 30 Doradus dominates the radio continuum emission in LMC at 1.4 GHz (see also Murphy et al. 2012; Foreman et al. 2015). These emissions occur when relativistic particles interact with the magnetic field and matter, and confirm the presence of CRs in ISBs. It is then reasonable to ask to what extent CRs affect the dynamics and evolution of ISBs.

There is yet another motivation to study the effect of CRs on ISBs. At a larger length-scale, it has been suggested that CRs can dynamically affect galactic winds (Booth et al. 2013; Salem & Bryan 2014; Simpson et al. 2016; Wiener, Pfrommer & Oh 2017). However, the detailed physics is not clearly understood. Firstly, changing the adiabatic index of the gas from 5/3 to 4/3 (i.e. replacing thermal pressure by CR pressure) reduces the size of ISBs (e.g. see Equation (4) in Gupta et al. 2018; also see Chevalier 1983). Secondly, diffusion of CRs would tend to decrease the pressure gradient, and therefore reduce the dynamical effect of CRs. We propose to study these processes in an ISB, which may help us to understand the effects at a larger length-scale.

In an earlier work, we studied the effect of CRs in an idealized ISB (Gupta et al. 2018). We found that the effect of CRs mainly depends on the CR injection region, diffusion coefficient and the shock Mach number. CRs can be injected in two different ways. In one case, CRs are injected at spatially resolved shocks whereas in the other case, it is assumed that a small fraction (~ 10%) of the wind/supernovae energy directly goes to CRs via internal shocks (these internal shocks may originate due to stellar flares, colliding winds and supernovae which are difficult to resolve in numerical simulations). The basic difference in (spatially resolved) shock injection and central injection of CRs is that, in the latter case, the back reaction from CRs at the shock can modify the thermodynamic properties of the shock when the Mach number exceeds ~ 12 (Drury & Völk 1981; Drury & Falle 1986; Becker & Kazanas 2001). In this case most of the upstream kinetic energy goes into CRs. This is how diffusive shock acceleration is captured in a two-fluid model. We estimated various relevant time-scales for the CR affected bubbles (see sections 2.2, 4.2 in Gupta et al. 2018). We showed that CR dominated ISBs may contain comparatively cool thermal plasma (temperature ~ 10^6-K), even in the absence of thermal conduction (which can also reduce the interior temperature of an ISB).

In this paper, we extend our work to determine the multi-wavelength signatures of ISBs arising from the presence of CRs, with the help of 1D and 3D numerical simulations. This will help us to compare our findings with observations of ISBs in different wavelengths, and to constrain the CR injection parameters.

We focus on the early evolution (≤ 4 Myr) when mechanical wind from a compact star cluster can form a reverse (termination) shock. We do not include supernova explosion (e.g. Sharma et al. 2014; Kim & Ostriker 2015; Yadav et al. 2017; Vasiliev, Shchekinov & Nath 2017) or large spatial separation of stars, which may change the evolution and structure of the ISBs. We start with an analytic estimates of different luminosities for a two-fluid ISB in §2. In §3 we discuss some recent results from ISB observations. This helps us to set-up our simulation, as discussed in §4. The results are presented in §5 and §6, and summarized in §7.

## 2 ANALYTICAL ESTIMATES

We consider an idealized two-fluid model of an ISB (for details, see Gupta et al. 2018). We wish to estimate the γ-ray, X-ray and radio luminosities, considering that CRs are being accelerated in an ISB.

### 2.1 γ-ray

The nature of γ-ray emission depends on the interaction mechanism between CRs and matter (Mannheim & Schlickeriser 1994).

#### 2.1.1 Hadronic origin

To estimate γ-ray luminosity due to hadronic interaction, we use the analytical prescription of Pfrommer & Enßlin (2004), which is briefly discussed below.

The γ-ray luminosity in (Eγ1 – Eγ2) energy band can be estimated using

\[
L_{\gamma}^{1} = \int_V dV \int_{E_{\gamma1}}^{E_{\gamma2}} dE_\gamma \int_{nN} q_\gamma(n_N, c_{cr}, E_\gamma) (\sigma_{pp} C E_p^{\alpha_p} v_{pp})^{-\alpha_p} \left[ \frac{E_p}{E_{\gamma}} \right]^{\delta_p} \left[ \frac{2 E_p}{E_{\gamma} v_{pp}} \right]^{-\delta_p} \left[ \frac{E_p}{E_{\gamma}^{2/3}} \right]^{1-\alpha_p} \beta(\alpha_p - 2, \frac{3-\delta_p}{2})
\]

where \(q_\gamma = dN/(dt dV dE_\gamma)\) is the number of γ-ray photons emitted per unit volume per unit time per unit energy, which is proportional to \(n_N\) (the number density of target nucleons) and \(c_{cr}\) (the CR energy density), and \(\Delta V\) is the volume of the emitting region. The function \(\tilde{q}_\gamma\) is given as,

\[
\tilde{q}_\gamma = \left[ \frac{\sigma_{pp} C E_p^{\alpha_p} v_{pp}}{E_{\gamma}^{2/3}} \right]^{-\alpha_p} \left[ \frac{E_p}{E_{\gamma}} \right]^{\delta_p} \left[ \frac{2 E_p}{E_{\gamma} v_{pp}} \right]^{-\delta_p} \left[ \frac{E_p}{E_{\gamma}^{2/3}} \right]^{1-\alpha_p} \beta(\alpha_p - 2, \frac{3-\delta_p}{2})
\]

Here \(E_p/E_{\gamma0}\) is the rest mass energy of proton/pions (π0), \(\alpha_p\) and \(\alpha_\gamma\) are the spectral indices of the incident CR protons and emitted γ-ray photons respectively, \(\delta_\gamma = 0.14 \alpha_\gamma 1.6 + 0.44\) is
the spectral shape parameter and $\sigma_{pp} = 32(0.96 + e^{4.4 - 2.4a})$ mbar (see Equations (8), (19)-(21) in Pfrommer & Enßlin 2004).

From Equation (1), we find that the result of the integration from 0.1 to 200 GeV energy is $\approx 1.1 \times 10^{-16} \text{ cm}^3 \text{s}^{-1}$ and it depends weakly (error $< 20\%$) on the choice of $a$, $\alpha_{\gamma}$, and $\alpha_{\nu}$ ($2.1 - 2.5$) when $\alpha_{\gamma} = \alpha_{\nu}$ (e.g. Dermer 1986). The $\gamma$-ray spectrum beyond 200 GeV differs from model to model, and we have, therefore, excluded it from our analysis. We thus obtain the $\gamma$-ray luminosity in $\approx (0.1 - 100)$ GeV band:

$$L_{\gamma}^H \approx 1.1 \times 10^{-16} \left( \frac{\Delta V}{\text{cm}^3} \right) \left( \frac{n_N}{\text{cm}^{-3}} \right) \left( \frac{\epsilon_{\text{cr}}}{\text{erg cm}^{-3}} \right) \text{ erg s}^{-1}.$$ \hspace{1cm} (3)

Clearly $L_{\gamma}$ is directly proportional to the target nucleon ($n_N$) and the CR energy density ($\epsilon_{\text{cr}}$), and therefore, the $\gamma$-ray emission arises from the denser region of the ISBs, e.g. the swept-up ambient medium (shell).

Consider the ambient density profile to be $\rho(\tau) = \rho_c (r_c/r)^\alpha$ where $\rho_c/r_c$ is the core density/radius of the ambient medium. We denote the CR pressure fraction in the shell as $W_{sh} = P_{\text{cr}}/\left( P_{\text{sh}} + P_{\text{cr}} \right)$ where $P_{\text{cr}}/P_{\text{sh}}$ is the volume averaged CR/thermal pressure in the shell. From the self-similar evolution of the bubble we obtain

$$L_{\gamma}^H = A \int V \left( \frac{r_c}{r} \right)^3 \left[ \frac{21}{\pi} - 6s \right] \left[ \frac{\gamma - 1}{3 - s} \right] \left[ \frac{(5 - s)^3}{(3 - s)^2} \right] \right] \left( \frac{r_c}{r} \right)^{5 - 2s}$$ \hspace{1cm} (4)

where

$$A = \frac{13.2 \pi \times 10^{-16}}{m_{\text{H}}} \left( \frac{21 - 6s}{(5 - s)^2 (3 - s)^2} \right)$$ \hspace{1cm} (5)

Here we have used Equations (4) and (5) in Gupta et al. (2018) to estimate the shell volume $\Delta V = 4\pi R^2 \Delta R$, $\Delta R$ is the shell width and $R$ is the radius of the ISB and target density $n_N \approx 4 \times \rho(0.1 \text{ GeV/m})$. We also have taken CR energy density $\epsilon_{\text{cr}} = P_{\text{cr}}/\left( \gamma_{\text{cr}} - 1 \right)$ where $\gamma_{\text{cr}} = 4/3$.

Equation (4) shows that, for a fixed1 $W_{sh}$, the time evolution of $\gamma$-ray luminosity depends on the ambient density power-law index $r_c$. If $5 > s > 5/4$, then $L_{\gamma}^H$ decreases with time. This is reasonable because the density falls so rapidly that only small column density targets are available for hadronic interaction. For $s < 5/4$, $L_{\gamma}^H$ is an increasing function of time. This means that, in principle, one can explain the observed luminosity with a small $W_{sh}$ by taking longer dynamical time. However in practice, the dynamical time is not a free parameter, because it is well constrained by the bubble radius and shell speed. Therefore, the modeling of the ambient density profile is crucial to interpret $\gamma$-ray observation.

### 2.1.2 Leptonic origin

Low energy photons ($\lesssim 1 \text{ GeV}$) which come from stars and/or Cosmic Microwave Background (CMB) radiation can gain significant energy via inverse Compton scattering with relativistic electrons. These secondary photons can be a possible source of $\gamma$-rays in ISBs.

Suppose the incident photons are dominated by stellar radiation with energy $E_{\text{incident}} \sim 0.01 - 100 \text{ eV}$ (far infrared to extreme UV). The corresponding Lorentz factor of relativistic electrons, require to enhance the energy of stellar photons to $E_{\text{obs}} \approx 0.1 - 100 \text{ GeV}$, is spread over $\Gamma \approx (E_{\text{obs}}/E_{\text{incident}})^{1/2} \approx 10^4 (\Gamma_{\text{min}} - \Gamma_{\text{max}})$. Assuming the number density distribution of relativistic electrons is $n(\Gamma) = \kappa_{1} \Gamma^{-p} (p \approx 2.2$ is the spectral index of relativistic electrons), we estimate the $\gamma$-ray luminosity ($L_{\gamma}^C$) from (see Equation 7.21 in Rybicki & Lightman 1979)

$$L_{\gamma}^C = \int V \left( \frac{4}{3} \sigma_T c \epsilon_{\text{ph}} \frac{\Gamma_{\text{max}}^3 - \Gamma_{\text{min}}^3}{\Gamma_{\text{min}} - \Gamma_{\text{max}}} \right)$$ \hspace{1cm} (6)

where $\epsilon_{\text{ph}}$ is the stellar radiation energy density and $\sigma_T$ is the Thomson cross-section. The normalization constant $\kappa_{1}$ is obtained from the energy density of CR electron $\epsilon_{\text{cr}}$ as,

$$\kappa_{1} \approx \frac{\epsilon_{\text{cr},0}}{m_e c^2} (p - 2) \left( \frac{1}{\Gamma_{\text{L}}^2} - \frac{1}{\Gamma_{U}^2} \right)$$ \hspace{1cm} (7)

Here, the lower and upper cutoff of Lorentz factor can be set to $\Gamma_{\text{L}} \rightarrow 1$ and $\Gamma_{\text{U}} \rightarrow \infty$. We assume the energy density of relativistic electrons $\epsilon_{\text{cr},0} \approx \epsilon_{\text{cr}} (m_e/m_p)^{(3-p)/2}$ (Persic & Rephaeli 2014). For $p \approx 2.2$, this gives $\epsilon_{\text{cr},0} \approx 0.05 \epsilon_{\text{cr}}$.

The stellar radiation energy density $\epsilon_{\text{ph}}(r)$ depends on the distance from stars and radiation luminosity ($L_{\text{rad}}$). Assuming that the stars are confined in a small region and that the total radiation luminosity $L_{\text{rad}} \sim 500 L_{\text{sw}}$ ($L_{\text{sw}}$ is the wind power) [Leitherer et al. 1999], $\epsilon_{\text{ph}}$ at a distance $r$ can be obtained from,

$$\epsilon_{\text{ph}}(r) = \frac{L_{\text{rad}}}{4 \pi r^2 c} \approx 435 \left( \frac{L_{\text{sw}}}{5 \times 10^{38} \text{erg s}^{-1}} \right) \left( \frac{r}{10 \text{pc}} \right)^{-2} \text{ eV cm}^{-3},$$ \hspace{1cm} (8)

which is much larger than the energy density in CMB photons $\sim 0.3 \text{ eV cm}^{-3}$. Using Equation (6), we find that the $\gamma$-ray luminosity in $0.1 - 100 \text{ GeV}$ energy due to inverse Compton scattering is

$$L_{\gamma}^C \approx 172 \times 10^{-16} \frac{L_{\text{sw}}}{\left( 5 \times 10^{38} \text{erg s}^{-1} \right)} \left( \frac{r}{10 \text{pc}} \right)^{-2} \epsilon_{\text{cr}} \text{ erg s}^{-1},$$ \hspace{1cm} (9)

where $dV$ and $\epsilon_{\text{cr}}$ are in CGS units.

Taking2 $n_N \approx 4\pi (r_c/r)^\alpha/m_{\text{H}}$ where $\rho_c = 220 m_{\text{H}} \text{ cm}^{-3}$, $r_c = 5 \text{ pc}$ and $s = 1$ (c.f. Figure 1), Equations (3) and (9) give

1 Depending on CR injection model, $W_{sh}$ may evolve with time, discussed in section 5.1.1.

2 Observations of ISBs suggest that the column density is $L \sim 10^{21 - 22} \text{ cm}^{-2}$ (e.g. Kim et al. 2003; Murphy et al. 2012). For a typical ISB with radius, say $R \sim 10 \text{ pc}$, number density $\approx L/R \sim 32 - 320 \text{ cm}^{-3}$. 

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the ratio of hadronic to Leptonic $\gamma$-ray luminosity:

$$\frac{L_{\gamma}^H}{L_{\gamma}^L} \approx 2.6 \left( \frac{\rho_c}{220 \text{m}_\odot \text{cm}^{-3}} \right) \left( \frac{L_w}{5 \times 10^{38} \text{erg s}^{-1}} \right)^{-1} \left( \frac{r}{10 \text{pc}} \right)^{-2}$$

This suggests that both hadronic and leptonic interaction can be important to explain observed $\gamma$-ray photons in ISBs, although $L_{\gamma}^H$ dominates for large bubbles.

### 2.2 X-ray

X-ray emissions depend on the inner structure of the ISB. For a qualitative understanding of X-ray luminosity ($L_x$), we consider the emission to be due to thermal bremsstrahlung which yields,

$$L_x = \int \nu dV \left[ 1.4 \times 10^{-27} Z^2 g_B n_e n_i T_{1/2} \right]$$

We take $Z \approx 1$, $g_B = 1.2$ and $n_e \approx n_i \approx P_{th}/(k_B T)$ and obtain

$$L_x \approx 3.7 \times 10^5 R^3 T_3^{-3/2} P_{th}^2$$

$$\approx 3.1 \times 10^{34} \left( \frac{R}{10 \text{pc}} \right)^3 \left( \frac{T}{5 \times 10^7 \text{K}} \right)^{-3/2} \times \left( \frac{P_{th}}{10^{31} \text{erg s}^{-1}} \right)^2 \text{erg s}^{-1}$$

In case of CR acceleration, $P_{th}$ will be smaller than in the one-fluid case, which may change $L_x$. Therefore, the X-ray luminosity is an important diagnostic to identify a CR dominated bubble.

### 2.3 Radio

We also wish to estimate the synchrotron emission rate from relativistic electrons. We consider the number density distribution of relativistic electrons to be $n(E) = \kappa_2 E^{-p}$. Note that the normalization constant, $\kappa_2$, is different from $\kappa_1$ of Equation (7). Denoting the magnetic field by $B$, the synchrotron volume emissivity is given by (see equation (8.131) in Longair 2011),

$$j_\nu \approx 2.3 \times 10^{-25} a(p) B^{(p+1)/2} \kappa_2' \nu^2 \times \left( \frac{3.217 \times 10^{42}}{\nu} \right)^{(p-1)/2} \frac{J \text{s}^{-1} \text{m}^{-3} \text{Hz}^{-1}}$$

Here $a(p) \approx 0.45$ for $p = 2.2$ (table 8.2 in Longair 2011), the magnetic field $B$ in Tesla, $\kappa_2 \approx (p-2) (m_e c^2)^{p-2} (c_{e\gamma})$ in $J^p \text{m}^{-3}$, and $\kappa_2'$ is obtained from $\kappa_2$ after a unit conversion to (GeV)$^{p-1} \text{m}^{-3}$.

Therefore, the luminosity per unit frequency is

$$\frac{dL_R}{d\nu} = \int_\nu dV j_\nu$$

$$\approx 1.4 \times 10^{24} \left( \frac{R}{10 \text{pc}} \right)^3 \left( \frac{B}{40 \mu \text{G}} \right)^{1.6} \times \left( \frac{\epsilon_{e\gamma}}{10^{-10} \text{erg cm}^{-3} \text{s}^{-1}} \right)^{0.6} \text{erg s}^{-1} \text{Hz}^{-1}$$

In the following sections we use numerical simulations to determine these observables using more realistic analysis.

### 3 OBSERVATIONS OF ISBS

In Table 1, we show the results from multi-wavelength observation of four massive star clusters. Column [2] shows that the wind power ranges between $10^{38} \lesssim L_w/(\text{erg s}^{-1}) \lesssim 10^{39}$. Column [3] shows the radius ($R$) of the bubble ($\sim 10-100 \text{ pc}$) and their dynamical age ($\lesssim 5 \text{ Myr}$). The details of $\gamma$-ray and X-ray observations are listed in columns [4] and [5] respectively. These indicate that $\gamma$-ray luminosity ($L_\gamma$) $\lesssim 10^{-3} L_w$ and the X-ray luminosity $L_x/L_w \sim 10^{-3} - 10^{-2}$. For all sources, the $\gamma$-ray spectral index in 0.1 – 200 GeV energy band is $\approx 2.2$. Column [6] shows that the radio power from 30 Doradus at 1.4 GHz is $dL_R/d\nu = 4\pi D^2 F_\nu \sim 1.7 \times 10^{26} \text{erg s}^{-1} \text{Hz}^{-1}$ (by taking $D \approx 50 \text{ kpc}$) [Hughes et al. 2007; see also Figure 5 in Foreman et al. 2015].

Note that, out of these objects, 30 Doradus is the only one in which most of the massive stars are located at the center and the structure of the bubble is close to spherical.
This motivates us to compare our results with 30 Doradus, which is discussed in §6.3.

4 SIMULATION SET-UP

We use a modified version of the PLUTO to perform hydrodynamic simulations in the presence of a CR fluid (Mignone et al. 2007; Gupta et al., in preparation). The following equations are solved:

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = S_{\rho} \tag{15}
\]

\[
\frac{\partial \rho \vec{v}}{\partial t} + \nabla \cdot (\rho \vec{v} \otimes \vec{v} + p_{\text{tot}}) = \rho \vec{g} \tag{16}
\]

\[
\frac{\partial e_{\text{tot}}}{\partial t} + \nabla \cdot \left[ (e_{\text{tot}} + p_{\text{tot}}) \vec{v} + \vec{F}_{\text{tot}} \right] = \rho \vec{v} \cdot \vec{g} + \rho \frac{\partial e_{\text{cr}}}{\partial r} \tag{17}
\]

\[
\frac{\partial e_{\text{cr}}}{\partial t} + \nabla \cdot \left[ (e_{\text{cr}} + p_{\text{cr}}) \vec{v} + \vec{F}_{\text{cr}} \right] = \vec{v} \cdot \vec{g}_{\text{cr}} + \rho_{\text{eff}} - \rho_{\text{cr}} \tag{18}
\]

Here $\rho$ and $\vec{v}$ are the mass density and fluid velocity respectively, $p_{\text{tot}} = p_{\text{th}} + p_{\text{cr}}$ is the sum of thermal and CR pressures, $e_{\text{tot}}$ is the sum of kinetic ($e_k$), thermal ($e_{\text{th}}$) and CR ($e_{\text{cr}}$) energy densities. The adiabatic index for the respective fluids are chosen as $\gamma_{\text{th,cr}} = 5/3, 4/3$. We have used HLL Riemann solver, piecewise linear reconstruction and RK2 time stepping. The CFL number is taken as 0.3.

4.1 Ambient medium

The typical size of giant molecular cloud is $\sim 10 - 100$ pc and masses are $\sim 10^4 - 10^6$ $M_\odot$. Detailed observations suggest that the cloud mass and radius follow $M_{\text{cl}} \propto R_{\text{cl}}^2$, i.e., the density profile ($\rho$) $\propto r^{-1}$ (Solomon et al. 1987; Hughes et al. 2010; Pfalzner 2016). In order to model this, we consider a self-gravitating gas cloud.

The most popular choice for a self-gravitating cloud is an isothermal sphere. A fit for the density profile in this case is given by Natarajan & Lynden-Bell (1997),

\[
\rho(r, r_c) = \rho_c \left[ \frac{5}{1 + (r/r_c)^2/10} - \frac{4}{1 + (r/r_c)^2/12} \right] \tag{19}
\]

Here $r_c = c_s/(4 \pi G \rho_c)^{1/2} = \left[ k_B T/(4 \pi G \rho_c \mu m_H) \right]^{1/2} \approx 2.2 T_{\text{eff}}^{1/2} \rho_c^{-1/2}$ pc is the core radius, $T$ is the temperature, $\rho_c$ is the core density and $\mu = 1.26$ (cold neutral medium). However, this profile does not give $\rho \propto r^{-1}$. We, therefore, relax the isothermal assumption on the global lengthscale ($\sim 100$ pc) of the cloud. Instead, we add several self-gravitating isothermal clouds and obtain a resultant density profile from,

\[
\rho(r) = \sum_{i=1}^{n} \rho(r, r_i) \tag{20}
\]

where we set the core density and temperature of the clouds as

\[
\rho_i = 2^{i-1} \times 10 m_H \text{ cm}^{-3}, \quad T_i = \frac{1600}{25-i} \text{ K} \tag{21}
\]

where $i = 0, 1, 2, ..., 8$ ($n = 8$). This profile provides a dense core ($\approx 620 m_H \text{ cm}^{-3}$) with temperature $\approx 200$ K and a mean surface density $\Sigma \approx 50 M_\odot \text{ pc}^{-2}$, see the comparisons of different ambient profiles in Figure 1.

To maintain hydrostatic equilibrium, we take into account the self gravity of the individual clouds. The net gravitational acceleration $\vec{g}$ (see Equations (16) and (17)) is obtained as,

\[
\vec{g}(r) = \sum_{i=1}^{n} \rho(r, r_i) \left[ \frac{\left(\epsilon_i^2\right)^2}{\rho(r, r_i)} \frac{d}{dr} \rho(r, r_i) \right] \hat{r} \tag{22}
\]
We find that the ambient profiles are stable for a few hundred Myr.

Note that the cloud profile obtained here is not unique. One can choose a different set of parameters to obtain different ambient density profiles. Furthermore, in a realistic scenario, the ambient medium consists of high density clumps ($\gtrsim 10^4 m_H$ cm$^{-3}$). Therefore, our ambient profile should be treated as a directionally averaged cloud profile.

### 4.2 Wind-driving region

For the runs performed in 1D spherical geometry, we choose a spherical region of radius $r_{inj} = 1$ pc around $r = 0$ and set a fine spatial resolution ($\Delta r = 0.05$ pc). This allows us to minimize nonphysical cooling losses at the early stages of shock formation (see section 4 in Sharma et al. 2014, also see Equation (10) in Gupta et al. 2016). In our fiducial set-up, we set $M = 4 \times 10^{-4} M_\odot$ yr$^{-1}$ and $L_w = 5 \times 10^{38}$ erg s$^{-1}$ which have been added uniformly (i.e. $S_p = M/V_{inj}$ and $S_e = L_w/V_{inj}$ where $V_{inj} = 4\pi r_{inj}^3/3$). Therefore, at the sonic point ($r = 1$ pc), the wind velocity is 1414 km s$^{-1}$ which asymptotically approaches $v_w = (2L_w/M)^{1/2} \approx 2000$ km s$^{-1}$ (Chevalier & Clegg 1985). We discuss the dependence of our results on these parameters in section 6.1.

To test the reliability of our fiducial 1D model, we perform 3D simulation, particularly to study the effects of distributed stars. For these runs we use Cartesian geometry and distribute a total of $N_{\star} = 500$ (assumed) injection points by using a Gaussian random number generator with zero mean value and the standard deviation of 1 pc (c.f. Figure 4). The radius of the injection points is taken as $\delta r_{inj} = 0.3$ pc, where mass and energy are added uniformly (similar to 1D). The spatial resolution in the central region, $[x, y, z] \in (-5, 5)$ pc, which covers all injection points, is set to 0.125 pc.

### 4.3 CR injection

We use the following two scenarios for CR injection:

- Injection in the wind-driving (IWD) region: Internal shocks in the wind-driving region can be efficient site for CR acceleration. However, it is difficult to spatially resolve them. To investigate this type of acceleration scenario, we use a parameter $\epsilon_{cr}$ to denote the fraction of wind energy injected into CRs. The fiducial value is $\epsilon_{cr} = 0.1$.
- Injection at the shock (ISH): In this case, we have injected CRs directly at the resolved shocks (i.e. at forward and reverse shock of the ISB). To identify whether a computational zone is shocked or not, we use the following conditions.

  
  
  (i) $\nabla \cdot \vec{\nu} < 0$,

  (iii) $\Delta x [\nabla p]/p \geq \delta_{\text{tolerance}}$

  (iii) $\nabla \cdot T \nabla \rho > 0$.

  In this work we have taken $\delta_{\text{tolerance}} = 1.5$. The last condition helps to exclude spurious oscillations at the contact discontinuity which can be detected as a shock (Pfrommer et al. 2017). We then find the total non-kinetic energy density of the shocked zone (i.e., $\epsilon_{th} + \epsilon_{cr}$) and re-distribute it by a parameter $\epsilon_{cr}^{\text{ISH}}$ such that the CR pressure fraction of the shocked zone $w = p_{cr}/(\rho_{th} + p_{cr}) = \epsilon_{cr}^e/(2 - \epsilon_{cr}^e)$.

  Note that the fraction of energy transfer depends on the location of the grid point, which is not necessarily the peak location (density/pressure) of a shock. This may reduce the effective post shock CR pressure (which determines the CR pressure fraction $W_{inj}/W_{sh}$ in the interior/shell) from the injected value ($w$).

  In both injection models, we ensure that CR injection does not add any additional energy in the computational zone. We simply distribute a fraction of the mechanical energy (by using $\epsilon_{cr}$ or $w$) in the form of CRs either in the wind-driving region or at the shocks.

### 4.4 Microphysics

#### 4.4.1 Cooling losses and heating

Cooling loss of the thermal fluid is taken into account by using a tabulated cooling function for the gas metallicity $Z = 0.4 Z_\odot$. To mimic photo-ionization heating from the central radiation field, we turn off cooling when temperature $T < 10^4$ K.

The corresponding collisional heating rate of the shocked zone is given as 2.6 $\times 10^{-16}$ $n_{\text{H}}$ $\epsilon_{cr}$ erg cm$^{-3}$ s$^{-1}$ (see section 2.1 in Guo & Oh 2008). The corresponding collisional heating rate of thermal gas is taken into account by using a tabulated cooling function for the gas metallicity.

| Parameter | Fiducial | Range covered |
|-----------|----------|---------------|
| $L_w$ (erg s$^{-1}$) | $5 \times 10^{38}$ | $10^{38} - 10^{39}$ |
| $v_w$ (km s$^{-1}$) | 2000 | $\approx 1000 - 5000$ |
| $\epsilon_{cr}$ | 0.1 | 0.01 - 0.20 |
| $w$ | 0.33 | 0.05 - 0.54 |
| $\kappa_{cr}$ (cm$^2$ s$^{-1}$) | $5 \times 10^{26}$ | $5 \times 10^{25} - 3 \times 10^{27}$ |

* Resolution in the central region (§4.3).

Note that heating due to CR steaming may affect the thermal fluid more than collisional heating. However, it is not possible to include it in our hydrodynamic set-up. Further, we find that the effect of CR collisional heating is negligible in our set-up. The CR heating can be better studied with the help of MHD simulations.
4.4.2 Thermal conduction & CR diffusion

We assume that both thermal conduction (hereafter, TC) and CR diffusion are isotropic. We use thermal conduction (TC) to have the Spitzer value \(6 \times 10^{-7} T^{5/2} \) in CGS and also assume the saturated thermal conduction (see section 4.3 in Gupta et al. 2016). The fiducial value of CR diffusion coefficient is set to \( \kappa_{cr} = 5 \times 10^{26} \text{ cm}^2 \text{s}^{-1} \), unless otherwise mentioned (Gupta et al. 2018). For both cases, we choose STS method (Alexiades et al. 1996) to speed up the diffusion module.

5 RESULTS

In this section, we show the results from fiducial runs (see Table 2). We first discuss 1D simulations (section 5.1) and then compare them with 3D simulations (section 5.2).

5.1 1D runs

The structural difference between one-fluid and two-fluid ISBs has been discussed in Gupta et al. (2018) (see their section 4.2). Here we present the time evolution of multi-wavelength luminosities.

5.1.1 \( \gamma \)-ray luminosity

To obtain the \( \gamma \)-ray luminosity, we use Equation (3) and display the results in the left-most panel of Figure 2. The dashed and solid curves represent model with and without thermal conduction (TC).

The solid curve (without TC) in this figure shows that the \( \gamma \)-ray luminosity (hereafter, displayed by violet curves) in both injection models (denoted by circular symbol: IWD and diamond symbol: ISH) is an increasing function of time. This is expected because, as time evolves, the swept-up mass (in the shell) increases. We also see that the \( \gamma \)-ray luminosity for IWD model (circular symbols) evolves differently from ISH model (diamond symbols). This can be understood from Equation (4) which shows \( L_\gamma \propto W_{\text{sh}}^{1/4} \gamma \). The parameter \( W_{\text{sh}} \) is the source of difference between the IWD and ISH models for the following reasons.

For IWD, when the Mach number of reverse shock becomes \( \gtrsim 12 \), most of the upstream kinetic energy is converted into CRs (Becker & Kazanas 2001; also see section 4.2 in Gupta et al. 2018). When TC is off (solid curve), this results in a large increase in CR pressure downstream of the reverse shock after \( t_{\text{dyn}} \gtrsim 2 \text{ Myr} \). These CRs diffuse and increase the CR pressure in the shell. Therefore, in the early stages of evolution, \( W_{\text{sh}} \) increases with time. This is illustrated in the subplot of the same panel. The run with TC (dashed curve) shows a similar result but with an earlier rise than without TC (\( t_{\text{dyn}} \gtrsim 0.5 \text{ Myr} \)).

On the contrary, for the shock injection scenario (ISH), \( W_{\text{sh}} \) is fixed. This causes a slower change with time. In this case, \( L_\gamma \) hardly shows any difference between with and without TC (compare the diamond symbols connected by solid and dashed lines).

5.1.2 X-ray luminosity

We use the Mekal plasma model (for gas metallicity \( Z = 0.4 Z_{\odot} \)) to estimate the X-ray luminosity in (\( \approx 0.5 - 2 \) keV range).
energy band and the results are displayed in the middle panel of Fig. 2.

Without TC (solid curves), the X-ray luminosity for all models is \( \approx 10^{34} \text{erg s}^{-1} \) (\( \sim 2 \times 10^{-5} L_w \)). To illustrate this, we recall Equation (12) which yields,

\[
\frac{L_x}{\text{erg s}^{-1}} \approx 1.7 \times 10^{37} T_7^{-3/2} \left[ \frac{\gamma - 1}{9 \gamma - 5} \right]^{5/4} (1 - W_{in})^2 \times L_{35}^{5/4} (\rho_c c_{e,5})^{3/4} t_6^{-1/4},
\]

(25)

where \( T \) and \( W_{in} \) denote the volume averaged temperature and CR pressure fraction inside the bubble respectively.

Without CRs, for our fiducial parameter \( T_7 \approx 5 \), Equation (25) gives \( L_x \approx 2.9 \times 10^{35} \text{erg s}^{-1} \) at \( t_{\text{dyn}} \approx 3 \text{Myr} \). However, in the simulation we find \( L_x \approx 1.5 \times 10^{34} \text{erg s}^{-1} \). The difference arises because \( T \) is outside of our range of interest (\( \approx 0.5 - 2 \text{keV} \)) and also because of cooling losses in the bubble (c.f. Figure 6).

The variation of \( L_x \) in different models is schematically shown in Figure 3. For the IWD model, due to an efficient energy transfer from thermal to CR fluid at the reverse shock, the temperature reduces to \( T_7 \approx 0.4 \) and \( (1 - W_{in})^2 \approx 10^{-2} \) (see figures 9 and 10 in Gupta et al. 2018), leading to \( L_x \approx 2 \times 10^{34} \text{erg s}^{-1} \). In contrast, \( L_x \) in ISH model depends on \( W_{in} \) (a larger \( w \) corresponds to smaller \( L_x \)) (see diamond and pentagon symbols in Figure 2).

A noticeable difference between IWD and ISH models is found when we include TC, displayed by the dashed curves in the middle panel of Fig. 2. In the absence of CRs, TC reduces the temperature without affecting the thermal pressure of the SW region. This increases \( L_x \) (see Equation (25) with a smaller \( T_7 \)). With CR in the IWD model, the X-ray luminosity is \( \approx 10 \) times smaller than ISH and one-fluid models. This is because of diffusive acceleration at the reverse shock which diminishes the shocked wind temperature and also reduces the effect of thermal conduction. For ISH model, \( L_x \) depends on \( W_{in} \), and for our choice of \( w = 0.33 \), \( L_x \) can be large (\( L_x \gtrsim 10^{-3} L_w \)).

5.1.3 Radio

We use Equation (13) to model the synchrotron radio emission. Since we do not include magnetic field (\( B \)) in our runs, we use two different methods to estimate the magnitude of \( B \).

The first method uses equipartition of magnetic energy with kinetic (\( ke \))/thermal (\( th \))/CR (\( cr \))/total energy (\( tot \)). The second method is motivated by observations that suggest that the magnetic field in a cloud depends on density (Valle 1993). Therefore, the magnetic field (\( B \)) has been estimated using,

\[
|\vec{B}| \approx \left\{ \begin{array}{ll}
\sqrt{8\pi x e} & \text{where } x : ke/th/cr/tot
\end{array} \right.
\]

(26)

where, the subscript ‘i’ stands for the initial ambient value. For simplicity, we assume \( B_i = 10 \mu \text{G} \) to be uniform. Due to ambiguity in magnetic field, we have five degenerate values of \( L_B \) (\( \equiv v dL_v / dv \)), at a given time. The result is shown by different colours in the right-most panel of Figure 2. Here, we use the same symbols (line styles) to represent IWD and ISH (with/without TC) models.

For IWD model, \( L_{1.4GHz} \) is consistent with the analytical estimates (Equation (14)). The subplot (b) for ISH model shows that the results depend weakly on time. The difference between IWD and ISH models stems for the fact that the fractions \( W_{in} \) and \( W_{sh} \), which determine the CR electron energy density (\( e_{cr,5} \)), evolve differently in these two models. For details see sections 5.1.1 and 5.1.2.

The luminosities in all bands show a weak time dependence after \( \approx 2.5 \text{ Myr} \). This allows us to compare with observations and explore the parameter dependence without invoking a particular epoch (c.f. section 6).

5.2 3D runs

5.2.1 Structure and dynamics

To present a more realistic scenario, we perform 3D simulations with the same fiducial parameters (see Table 2). In these runs, mass and energy are injected in a distributed manner. Figure 4 displays the injection points where the horizontal colour palette represents the \( z \) coordinates of those points. The vertical colour palette displays the density snapshot in the \( z = 0 \) plane at 0.05 Myr. This shows that individual bubbles have started to merge at this epoch. At a later time (\( t_{\text{dyn}} \gtrsim 0.5 \text{ Myr} \)), the structure appears as an ISB, as shown in Figure 5.

The left panel of Figure 5 shows the snapshot of density profile at \( z = 0 \) plane for different models. The cumulative effect of all injection points produces a free wind profile followed by a reverse shock, shocked wind and forward shock.
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Figure 4. Distributed injection in 3D. The horizontal colour palette displays z-coordinate of the injection points (darker points are in the back, and brighter points in front). The vertical colour palette displays the snap shot of density profile in $z = 0$ plane at $0.05 \text{ Myr}$. The figure represents the early stage of bubble formation. Therefore, the structure is very similar\(^3\) to that of a classical ISB.

The size of the bubble carries useful information, e.g. the mass of the shell, the volume of X-ray cavity. Because of the distributed nature of injection points in 3D runs, the size evolution may be different. We show the comparison of 1D (grey curves) and 3D (blue curves) runs in Figure 6. For both geometries (i.e. spherical and Cartesian), we first estimate the swept-up mass ($M_{\text{sh}}$) and then we obtain the average shell radius by using:

$$R \approx \left[\frac{3 - s}{4\pi \rho_c r_c^4 M_{\text{sh}}}\right]^{1/(3 - s)}, \quad (27)$$

where $\rho_c = 220 \, m_H \, \text{cm}^{-3}$, $r_c = 5 \, \text{pc}$ and $s = 1$ (see Figure 1). From this figure we find that the radius of the bubble in 3D runs is smaller compared to 1D runs. Therefore, the 3D runs are expected to show a lower luminosity. Otherwise, the different CR injection models do not show significant change from the one-fluid bubble. Therefore, the dynamical impact of CRs in ISBs may not be important.

\(^3\) It is worth noting that the coherent reverse shock may be destroyed if energy is injected via exploding supernovae rather than our smooth stellar winds (see Sharma et al. 2014; Yadav et al. 2017).

5.2.2 Time evolution of luminosities

Following the methods described in sections 5.1.1, 5.1.2 and 5.1.3, we estimate $L_\gamma$, $L_X$ and $L_R$ for our 3D runs. For $\gamma$-ray, we compute both hadronic and leptonic components.

In Figure 7, the solid curves displaying $L_\gamma$ due to hadronic interaction show a similar time dependence as in 1D. The CR pressure fraction (see subplot) for the models IWD and ISH are $W_{\text{sh}} \approx 0.25$ and $W_{\text{sh}} \approx 0.17$ respectively.
The luminosity is somewhat lower than the 1D cases. This is because the size of the ISB is smaller than in 1D model\(^4\) (Figure 6). The dashed curves show that inverse Compton scattering is sub-dominant. The lower panels display the \(\gamma\)-ray surface brightness map (SB\(\gamma\)). SB\(\gamma\), due to hadronic and leptonic interactions are obtained from

\[
\frac{\text{SB}_\gamma}{\text{erg s}^{-1} \text{ cm}^{-2}} = \begin{cases} 
\int_{-L}^{+L} \frac{dz}{dz} \left[ 1.1 \times 10^{-16} \, n_N \, e_{cr} \right] \\
\int_{-L}^{+L} \frac{dz}{dz} \left[ 172 \times 10^{-16} \left( \frac{r}{10 \text{pc}} \right)^{-2} \, e_{cr} \right],
\end{cases}
\]  

respectively (see Equations (3) and (9)). The hadronic \(\gamma\)-ray maps (panels a1 and b1) indicate that central region of the bubble is not bright in \(\gamma\)-ray. In contrast, for leptonic \(\gamma\)-ray model (panels a2 and b2), the stellar radiation field increases the \(\gamma\)-ray brightness in central region. This can be a diagnostic to distinguish between the hadronic and leptonic models.

Figure 8 for X-ray luminosity shows that the one-fluid with TC model\(^5\) (pentagon symbol) \(L_x \approx 1.7 \times 10^{35} \text{ erg s}^{-1}\) at \(t_{\text{dyn}} \gtrsim 2 \text{ Myr}\). Removal of TC makes it dimmer by a factor of \(\sim 10\). For ISH model, \(L_x\) approaches \(1.5 \times 10^{35} \text{ erg s}^{-1}\), for our choice of small \(w\). \(L_x\) for the IWD model is close (difference \(\lesssim 3\)) to one-fluid ISB without TC. In other words, the presence of CRs can mimic the absence of thermal conduction.

The projection maps (obtained similarly as the \(\gamma\)-ray map) for respective models are displayed in bottom panels. The maps clearly show that for one-fluid model, thermal conduction can increase X-ray surface brightness (as illustrated in Figure 3). Consider now the effect of CRs. If the wind-driving region (IWD) is the main site for CR acceleration, the X-ray surface brightness is dimmer than shock injection model (ISH). Therefore, the surface brightness pro-
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6 DISCUSSIONS

In previous section we have studied the time evolution of γ-ray, X-ray and radio luminosities, and the difference between 1D and 3D models. Here we explore the dependence of our results on different parameters using 1D runs.

6.1 Wind velocity

Although the wind velocity ($\approx (2L_w/\dot{M})^{1/2}$) is a critical parameter, it does not have a well defined prescription. Figure 10 shows the dependence of our results ($L_\gamma$, $L_x$ and $L_R$ in top, middle and bottom panels) on this parameter for the IWD case.

The top panel of Figure 10 displays $L_\gamma$. Two different line-styles (dotted and dash-dotted), which represent $L_\gamma$ due to hadronic and leptonic interactions, indicate that the hadronic interaction dominates over inverse Compton scattering (section 2.1.2). When TC is off (see circles) and the wind velocity ($v_w$) is varied from from 1000 to 4000 km s$^{-1}$, the γ-ray luminosity changes by a factor of $\sim 2$. In contrast, for the models with TC (the diamond symbols), $L_\gamma$ is almost independent of $v_w$ (the violet curve).

The middle panel displaying the X-ray luminosity shows a significant dependence on $v_w$. A small $v_w$ indicates a large $\dot{M}$, correspondingly a large density, and it results in a high $L_x$. However, if $v_w$ is too small ($v_w \lesssim 1200$ km s$^{-1}$ and $\dot{M} \gtrsim 10^{-3}$ M$\odot$ yr$^{-1}$) then the shocked-wind region radiates so efficiently that it disappears and the X-ray emission is quenched ($L_x/L_w \ll 10^{-6}$).

The bottom panel shows the synchrotron emission at 1.4 GHz. This panel shows a moderate (within a factor of $\approx 2$) dependence on $v_w$.

In ISH model, all luminosities (not displayed) show a similar dependence on $v_w$ when TC is off. However, in runs with TC, the X-ray luminosity is $\gtrsim 10^{-3} L_w$, which is significantly higher than that in IWD model.

6.2 Star cluster mass & CR parameters

Here we explore the dependence on three important parameters. The first one is the mechanical luminosity ($L_w$) which
depends on cluster mass. The other two parameters are the CR injection fraction and diffusion coefficient. In all our runs discussed in this section thermal conduction is included.

6.2.1 Non-thermal pressure in the shell

We have estimated the volume averaged cosmic ray and thermal pressure in the shell for four different values of $L_w$, where the other parameters are kept identical to the fiducial run (Table 2). The dotted straight line in Figure 11 verifies that the CR pressure fraction, i.e., $W_{sh} = P_{cr}/(P_{th} + P_{cr}) \approx 0.17$ is fixed in ISH. In contrast, the dash-dotted curve (IWD) shows that the CR pressure fraction increases as $W_{sh} \propto L_\gamma^{0.45}$. This indicate that if the wind-driving region is an efficient site for CR acceleration (IWD) then for massive star clusters, CR pressure in the shell can be comparable to or larger than thermal pressure.

6.2.2 $\gamma$-ray, X-ray and Radio

In Figs. 12 and 13 we display the variation of $L_\gamma$, $L_\alpha$ and $L_R$ on all three parameters ($L_w$, $w/\epsilon_{cr}$ and $\kappa_{cr}$). The main plot shows the dependence on $L_w$, the subplots (a) and (b) show the dependence on CR injection fraction ($\epsilon_{cr}/w$) and diffusion coefficient ($\kappa_{cr}$) respectively.

- IWD (left panels of Figures 12 and 13): We find that $L_\gamma \propto L_w^{0.9}$, $L_\alpha \propto L_w^{0.9}$ and $L_R \approx v dL_R/dv \propto L_w^{1.3-1.7}$. The small variation of $L_\gamma$ can be understood from Equation (4) which yields $L_\gamma \propto W_{sh}^{3/2} L_w^{3/4}$. Since $W_{sh} \propto L_w^{0.45}$ (see Figure 11), we expect $L_\gamma \propto L_w^{3/2}$. However, in simulation we get a weaker dependence because for a low $L_w$ (i.e. a smaller bubble and high density ambient medium), the ambient contribution enhances $L_\gamma$. Important point to note is that $L_\alpha < L_w/10^4$ (blue). The subplot (a1) in both figures indicates that all luminosities are insensitive to the CR injection fraction ($\epsilon_{cr}$). The subplot (b1) shows that $L_\alpha$ and $L_\gamma$ are anti-correlated when $\kappa_{cr}$ is varied $5 \times 10^{25} \lesssim \kappa_{cr}/cm^2\ s^{-1} \lesssim 3 \times 10^{27}$. This is because a sufficiently large (or sufficiently small) $\kappa_{cr}$ diminishes the efficiency of CR re-acceleration (for details, see section 4.2 in Gupta et al. 2018) which increases $L_\alpha$ but decreases $L_\gamma$. We conclude that $L_\gamma$ can be as large as $\approx 5\%$ of $L_w$ only when $10^{26} \lesssim \kappa_{cr}/cm^2\ s^{-1} \lesssim 10^{27}$.

- ISH (right panels of Figures 12 and 13): Figures show...
Figure 12. Parametric study of γ-ray (violet) and X-ray (blue) luminosities. The violet and blue coloured vertical axes display $L_\gamma$ and $L_x$ respectively. The subplot (a1)/(a2) displays the dependence of results on the CR injection fraction ($\epsilon_{cr}$ or $w$), and (b1)/(b2) shows the dependence on the CR diffusion coefficient. The subplot (a1) shows that $L_\gamma$ and $L_x$ do not depend on the injection fraction. The subplot (b1), (a2) and (b2) indicate an anti-correlation of $L_\gamma$ with $L_x$.

Figure 13. Parametric study of the synchrotron radio luminosity per frequency ($dL/d\nu$) at 1.4 GHz. Due to ambiguity in magnetic field ($B$), $dL/d\nu$ is spread over the sky-blue shaded region. In both panels, $L_R (= \nu dL/d\nu)$ increases with $L_w$. The subplots (a1) and (b2) display that $L_R$ does not depend on $\epsilon_{cr}$ and $\kappa_{cr}$. The subplot (b1) (and (a2)) shows that $L_R$ decreases (increases) with $\kappa_{cr}$ ($w$).
that $L_\gamma \propto L_{w}^{0.75}$, $L_x \propto L_w^{1.2}$ and $dL_R/dv \propto L_{w}^{-1.4}$. The dependence of $L_\gamma$ and $L_x$ are therefore consistent with Equations (4) and (25). The subplot (a2) confirms that $L_\gamma$, $L_x$ and $L_R$ change almost linearly with the injection fraction ($w$). The subplot (b2) shows that $L_x$ increases with $\kappa_{cr}$. This is because we have used a fixed $w$ irrespective of $\kappa_{cr}$. A larger CR diffusion enhances the ambient contribution and hence it increases $L_\gamma$. In contrast, $L_x$ is changed only by a factor $\lesssim 2$ because in this model the interior of the ISB does not depend on $\kappa_{cr}$.

### 6.3 Comparison with Observation

We are now at a stage to compare with observation. Young star clusters ($\lesssim 3.5$ Myr) are powered mainly by stellar winds (Leitherer et al. 1999, see also Figure 1 in Gupta et al. 2016). If stars are distributed in a compact region then a coherent reverse (termination) shock is expected to form. Even if there are supernovae and massive transient winds from within the star cluster, we do not expect the scenario to change significantly as long as the energy deposited by the smooth winds dominates.

For 30 Doradus, most of the massive stars are located at the central few pc region (e.g. Massey & Hunter 1998; Selman et al. 1999). Table 1 shows that for 30 Doradus $L_\gamma/L_w \sim 10^{-2}$, $L_x/L_w \sim 2 \times 10^{-3}$ and $(dL_R/dv)/L_w \sim 8 \times 10^{-14}$ Hz$^{-1}$. This suggests that the forward and reverse shock injection model (ISH) is the most preferable one (see the right panels in Figures 12 and 13 with $L_w \approx 2 \times 10^{39}$ erg s$^{-1}$). We can also put an upper limit of $\lesssim 0.2$ on the ratio of CR pressure to thermal pressure in the photo-ionized shell (Figure 11). Moreover, our results also suggest that thermal conduction is indeed required to explain $L_x$, because without it $L_x/L_w \lesssim 10^{-4}$.

For other objects listed in Table 1, $L_\gamma/L_w \lesssim 10^{-3}$. The reason could be a low density ISM. However, their structures are quite irregular, and our simplified model may not be suitable for a meaningful comparison.

### 7 CONCLUSIONS

We have presented the detailed diagnostics of the $\gamma$-ray, X-ray and radio luminosities to understand the effects of CR in a young star cluster. This work is an extension of Gupta et al. (2018) which demonstrated the two-fluid model of an ISB. Our key results are:

(i) Ambient medium: We have modeled an ambient density profile (mean surface density $\sim 50 \, M_\odot$ pc$^{-2}$) that follows $M_\delta \propto R_\delta^2$ (§4.1, Figure 1). This profile makes the resulting $\gamma$-ray luminosity weakly dependent on time (§2.1.1), and allows a convenient comparison with observation.

(ii) ISB profiles: The structure of ISB plays a crucial role in the comparison with observations. We have focused on the early phases of bubble evolution ($\lesssim 4$ Myr; i.e. ISB is driven by the stellar wind, not supernovae), and show that 3D structure is consistent with 1D runs (Figure 5).

(iii) Dynamical effects of CRs: We compare bubble radius between with and without CR models by considering two different CR injection scenarios (models: IWD and ISH, §4.3). Our models do not show a noticeable difference in the bubble radius (Figure 6).

(iv) Multi-wavelength luminosities: We find that if central wind-driving (IWD) region accelerates CRs then $\gamma$-ray luminosity ($L_\gamma$) can reach $\approx 5\%$ of the wind mechanical power ($L_w$) when the reverse (termination) shock is CR dominated. In this scenario, $L_\gamma$ is almost independent of the CR injection fraction (Figure 12) and the X-ray luminosity $\lesssim L_w/10^{4}$. If the forward/reverse shock (ISH) of an ISB is the CR injection site, then the $\gamma$-ray luminosity is directly proportional to injection fraction ($w$) and X-ray luminosity ($\gtrsim L_w/10^{4}$) is reduced by a factor of $\sim 1-w^2$ from one-fluid model (Figure 12). We also show the expected range for the radio emission at 1.4 GHz (Figure 13).

(v) Comparison with observation: We compare our models with the well observed star cluster, 30 Doradus. We find that the CR injection at the reverse and forward shocks (ISH model) can explain multi-wavelength observations.

Therefore, we suggest that the comparison of the $\gamma$-ray, X-ray and radio luminosities with the wind mechanical power will help to know the details of CR acceleration in star clusters.

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APPENDIX A: NUMERICAL CONVERGENCE

We present resolution study for our 1D fiducial model in Figure A1. The dashed curves (IWD model without TC) show that $L_z$ is converged if the grid resolution $Δr ≲ 0.061$ pc (i.e. grid number $|w| ≲ 4096$). The difference in $γ$-ray luminosity between low ($Δr ≈ 0.5$ pc) and high ($Δr = 0.03$ pc) resolution runs is a factor of $≈ 4$. For the runs with TC (solid curves), $L_z$ is almost independent of grid resolution. The difference between with and without TC in the high resolution case is indistinguishable. It suggests including thermal conduction while studying the two-fluid model.

The right panel shows the X-ray luminosity (with TC) for five different resolutions. For ISH model, a low resolution run causes large cooling losses (see e.g. Yadav et al. 2017) resulting a smaller $L_x$. In IWD model, the bubble is CR dominated which does not cool as efficiently as thermal fluid, results a weaker dependence on $Δr$ than the ISH case. This figure shows that for IWD model $L_x/L_w ≲ 10^{-4}$.

For our 3D runs, $Δr ≈ 0.79$ pc (for $|x,y,z| ≥ 5$ pc) which is much larger than the spatial resolution used in our 1D simulations ($Δr ≈ 0.06$ pc). We have included thermal...
Figure A1. Resolution study for our 1D fiducial model. [Left panel] The time evolution of $L_\gamma$ in IWD model for five different grid resolutions (fiducial resolution $\Delta r \approx 0.061$ pc i.e. $n_{\text{grid}} = 4096$) where the size of the circle is proportional to grid spacing ($\Delta r$). Figure shows that for a low resolution run (i.e., $\Delta r > 0.061$ pc), $L_\gamma$ is converged if thermal conduction (TC) is on. [Right panel] Dependence of $L_x$ (with TC) on grid number ($\propto 1/\Delta r$). The circle and diamond symbols stand for IWD and ISH models respectively at 3 Myr. This figure shows that for IWD model $L_x/L_w \lesssim 10^{-4}$.

Conduction in order to get a numerically converged $L_\gamma$. However, $L_x$ is underestimated at this resolution because of the reason discussed above. The qualitative results of 3D runs are consistent with 1D runs.