

# Runaway stars as cosmic ray injectors inside molecular clouds

M.V. del Valle<sup>1,2\*</sup>, G.E. Romero<sup>1,2†</sup> and R. Santos-Lima<sup>3‡</sup>

<sup>1</sup>*Instituto Argentino de Radioastronomía, C.C.5, (1894) Villa Elisa, Buenos Aires, Argentina*

<sup>2</sup>*Facultad de Ciencias Astronómicas y Geofísicas, Universidad Nacional de La Plata, Paseo del Bosque, 1900 La Plata, Argentina*

<sup>3</sup>*Instituto de Astronomia, Geofísica e Ciências Atmosféricas, Universidade de São Paulo, São Paulo, SP 05508-090, Brazil*

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## ABSTRACT

Giant molecular clouds (GMCs) are a new population of gamma-ray sources, being the target of cosmic rays (CRs) – locally accelerated or not –. These clouds host very young stellar clusters where massive star formation takes place. Eventually, some of the stars are ejected from the clusters, becoming runaway stars. These stars move supersonically through the cloud and develop bowshocks where particles can be accelerated up to relativistic energies. As a result, the bowshocks present non-thermal emission, and inject relativistic protons in the cloud. These protons diffuse in the GMC interacting with the matter.

We present a model for the non-thermal radiation generated by protons and secondary pairs accelerated in the bowshocks of massive runaway stars within young GMCs. We solve the transport equation for primary protons and secondary pairs as the stars move through the cloud. We present non-thermal emissivity maps in radio and in gamma rays as a function of time. We obtain X-ray luminosities of the order  $\sim 10^{32}$  erg s<sup>-1</sup> and gamma-ray luminosities  $\sim 10^{34}$  erg s<sup>-1</sup>. We conclude that, under some assumptions, relativistic protons from massive runaway stars interacting with matter in GMCs give rise to extended non-thermal sources.

**Key words:** radiation mechanisms: non-thermal — ISM: clouds — gamma-rays: ISM

## 1 INTRODUCTION

Molecular clouds (MCs) are good targets for galactic cosmic rays (CRs) since they are extended regions with great amounts of mass. These systems contain particle accelerators such as supernova remnants (SNRs), OB massive stars and pulsars. The relativistic particles accelerated in these sources add to the galactic cosmic-ray population that illuminates the clouds producing gamma rays (e.g. Casse, Montmerle & Paul 1980; Aharonian & Atoyan 1996; Torres, Dame & Digel 2005).

GMCs are a new class of extended gamma-ray sources (e.g., Ackermann et al. 2012a; Fernandez et al. 2013). However, their potential as passive gamma-ray sources have been claimed since the beginning of gamma-ray astronomy and their emission was predicted in theoretical models long time ago (e.g. Kraushaar et al. 1972; Aharonian 1991; Combi & Romero 1995; Hunter et al. 1997). Not only passive GMCs emit gamma rays; recently the smaller and

gas-rich star forming regions Chamaeleon, R Coronae Australis, Cepheus and Polaris have been detected by *Fermi* (Ackermann et al. 2012b).

GMCs harbour young stellar clusters where massive stars form. Many stars with masses  $M > 8 M_{\odot}$  might be ejected from the clusters (e.g., Perets & Šubr 2012), becoming runaway stars travelling through the cloud. Runaway stars have spatial velocities  $> 30$  km s<sup>-1</sup> (e.g. Gies & Bolton 1986). Two mechanism have been proposed for the origin of the high velocities in these stars. In the binary-supernova scenario one of the stars in a binary system is expelled during the supernova explosion of its companion (Blaauw 1961). In the other scenario, the dynamical-ejection model, the star is expelled through close gravitational interactions between members of a cluster or association (Leonard & Duncan 1988). Currently the latter process is believe to be the most frequent (Fujii & Portegies Zwart 2011), but both mechanisms surely operate (Hoogerwerf, de Bruijne & de Zeeuw 2000).

The supersonic interaction between the wind of fugitive stars with the interstellar medium (ISM) produces a bowshock (e.g., van Buren & McCray 1988; Peri et al. 2012). The wind-swept material, gas, and dust is heated by the

\* E-mail: maria@iar-conicet.gov.ar

† E-mail: romero@iar-conicet.gov.ar

‡ E-mail: rlima@astro.iag.usp.br

shock and radiated away in the infra-red (IR) band (e.g., van Buren & McCray 1988; Kobulnicky, Gilbert & Kiminki 2010).

Both observational (Benaglia et al. 2010; López-Santiago et al. 2012; del Valle, Romero & De Becker 2013) and theoretical research (del Valle & Romero 2012, 2014) support the idea that bowshocks from massive runaway stars accelerate particles up to relativistic energies. Electrons lose their energy in the acceleration region, while protons escape, convected away by the shocked wind without losing much of their energy. The escaped protons then diffuse in the MC.

We propose here that protons accelerated in bowshocks from massive runaway stars embedded in MCs contribute to the cloud's cosmic-ray population that produces the observed gamma rays in these systems. The relativistic protons interact with the MC matter via  $p - p$  inelastic collisions (Aharonian & Atoyan 1996; Bosch-Ramon, Aharonian & Paredes 2005).

The favourite sources for accelerating particles in the ISM are SNRs, which can inject particles with total energies up to  $10^{50}$  erg; it is believed that these sources are responsible for the bulk of the galactic CRs (Ginzburg & Syrovatskii 1964; Hillas 2005). MCs near SNRs produce gamma emission (e.g., Combi, Romero & Benaglia 1998). Three H.E.S.S. sources are firmly associated with a MC-SNR system. However, in the star forming regions immersed in GMCs, besides SNRs, there exist very energetic sources such as young stars with powerful winds. A very massive star during its life (1-10 Myr) can inject into the ISM an amount of kinetic energy from its wind comparable to the SNR values. However, a young cluster has not lived enough time for a SNR to develop and to be able to inject relativistic particles into the cloud. Here we proposed that runaway massive stars<sup>1</sup> could contribute to the local density of relativistic particles inside MCs, and produce significant non-thermal emission. An instrument with both good enough sensitivity and angular resolution, such as the forthcoming Cherenkov Telescope Array (CTA, see Actis et al. 2011)<sup>2</sup> can detect the produced emission and its expected morphology, that we estimate in this work.

We organized this article as follows. In the next section we briefly introduce MCs and their gamma-ray emission. Section 3 deals with runaway stars in MCs. There we present the scenario adopted in this work. In Sec. 4 we describe the model and in Sec. 5 we describe the numerical method we use in the calculations. The results are given in Sec. 6. Finally, in Sec. 7 we discuss the results and offer our conclusions.

## 2 MOLECULAR CLOUDS

MCs are dense and cold regions that constitutes the most dense component of the ISM. They have temperatures of

<sup>1</sup> No evidence exists so far of a strong shock or of non-thermal emission from the bowshock of a low-velocity (non-binary) massive star. A strong shock might not form due to the catastrophic adiabatic wind losses (Voelk & Forman 1982). In a runaway star the stagnation point is much closer to the star.

<sup>2</sup> However, *Fermi*, in target mode, might have sufficient sensitivity to detect the emission.

the order of 10 to 20 K, and average densities of the order of  $10^2 \text{ cm}^{-3}$ . In these systems most of the new stars of the Galaxy are formed. Young stars are associated with the densest regions of the clouds ( $n > 10^4 \text{ cm}^{-3}$ ). In these cores of GMCs (with total masses between  $10^3$  and  $10^6 M_{\odot}$ ) the most massive stars are born.

In the Galaxy the molecular gas is typically concentrated in big complexes or segments of spiral arms with sizes of the order of  $\sim 1$  kpc and masses of  $10^7 M_{\odot}$ . These systems can contain many GMCs with sizes of  $\sim 100$  pc and masses of  $\sim 10^6 M_{\odot}$ . These GMCs also contain substructures such as the cores with sizes of the order of  $\sim 0.1$  pc. In our Galaxy smaller clouds also exist with masses of  $\sim 500 M_{\odot}$  (e.g., Larson 2003).

The clouds have structure and turbulence at all scales. The gas density in these objects varies many orders of magnitude, the densest regions having densities as high as  $\sim 10^5 \text{ cm}^{-3}$ . The density profile is not well known, with different substructures present in the clouds (filaments, clumps, cores, etc.). Usually, the following profile is adopted for the density (e.g., Gabici, Aharonian & Blasi 2007):

$$n(R) = \frac{n_0}{1 + \left(\frac{R}{R_n}\right)^{\beta}}, \quad (1)$$

where  $R$  is the distance from the cloud centre and  $R_n$  is the core radius. The index  $\beta$  is a free parameter.

MCs are magnetized, the magnetic field being important in their evolution and dynamics. The magnetic field is closely related to the gas density (Crutcher 1999), and it is described by the following profile:

$$B \sim 100 \left(\frac{n}{10^4 \text{ cm}^{-3}}\right)^{\eta} \mu\text{G}. \quad (2)$$

Here  $\eta = 0.5$ . Although the correlation given in Eq. (2) between the gas density and the magnetic field has been found for the cores of MCs with densities greater than  $10^3 \text{ cm}^{-3}$ , it provides reasonable values for regions of lower density and it is usually extrapolated to the whole range of densities (e.g., Gabici, Aharonian & Blasi 2007; Pedalotti et al. 2013), although this correlation can be substantially reduced by turbulence (Santos-Lima et al. 2010).

The average age of MCs is of  $\sim 10$  Myr (e.g., Bodenheimer 2011). The clouds are eventually destroyed and disrupted by ionization, outflows and winds produced by the young stars.

### 2.1 Gamma rays from molecular clouds

As mentioned above, some GMCs are gamma-ray sources. Studies of the gamma-ray emission of nearby MCs (at distances  $\sim 1$  kpc) dated since the *COS-B* days (e.g., Bloemen et al. 1984; Hunter et al. 1994). Theoretical works on the cosmic-ray illumination of nearby sources are even older (e.g., Black & Fazio 1973; Montmerle 1979). Diffuse gamma-ray emission has been detected from the galactic centre region, being spatially correlated with a GMC complex (Aharonian et al. 2006); star formation regions inside MCs also have been detected: Monoceros R2 (Martí et al. 2013), Westerlund 2 (Reimer et al. 2008), Westerlund 1 (Ohm, Hinton & White 2013), the region of

Cygnus (Aharonian et al. 2005), and the Orion region, which includes three dense young star clusters (Hartmann 2009). Additionally, *Fermi* has been detecting nearby clouds (at distances  $d < 300$  pc) in the energy range 250 MeV–10 GeV; these clouds have masses between  $10^3 - 10^4 M_\odot$  (Ackermann et al. 2012b). The gamma-ray luminosities observed in MCs vary between  $\sim 10^{33}$  and  $10^{35}$  erg  $s^{-1}$ .

Gamma-ray emission is of special interest because, when it is detectable, its study provides a good tool for investigating acceleration and propagation of CRs in the Galaxy (e.g., Aharonian 2001). MCs embedded in the galactic cosmic-ray sea are expected to emit gamma rays as passive sources. If particles can freely penetrate the clouds, the gamma-ray spectrum is expected to mimic the cosmic-ray spectrum and the total gamma-ray luminosity depends only on the total mass of the cloud (e.g., Gabici 2011). However, cosmic-ray penetration on MCs is a subject of debate. In general, the penetration might depend on the diffusion coefficient, a key parameter very hard to estimate both theoretically and observationally.

### 3 RUNAWAY STARS IN MOLECULAR CLOUDS

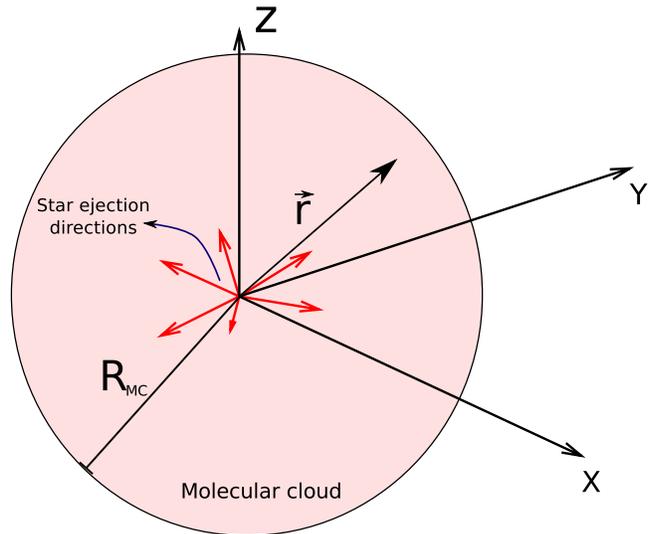
Numerical simulations and theoretical predictions indicate that many massive stars can be ejected with high velocities from their formation clusters by gravitational encounters. Runaway stars then move through their parental MC. The probability to eject a star from a massive cluster with velocity  $V_*$  is a power law  $\propto V_*^{-\nu}$ , where  $\nu = 3/2$  for slow runaways, and  $8/3$  for fast ones (Perets & Šubr 2012). Additionally, the ejection probability increases with mass. N-body simulations show that during its life a cluster can eject  $\sim$  six stars with masses  $> 8M_\odot$ , independently of the cluster mass (Fujii & Portegies Zwart 2011). Observational evidence consistent with these results is found, for example, in the R136 cluster: six massive runaway stars are associated with it (Gvaramadze, Kroupa & Pflamm-Altenburg 2010; Bestenlehner et al. 2011).

Stellar bowshocks inside MCs might not be detectable in the IR because the emission produced by the whole cloud overshines individual contributions. Nevertheless, the presence of bowshocks can be inferred through the study of certain spectral lines and masers. Masers are collisionally excited by hydrogen which is heated by shock waves (e.g., Elitzur 1976).

A runaway star moving through an inhomogeneous medium produces variable non-thermal emission (del Valle & Romero 2014). The electrons yield the bulk of the non-thermal radiation, while most of the accelerated protons escape without losing much of their energy and then diffuse in the environment. Gamma-ray emission and secondary electron-positron pairs are produced through  $p-p$  interactions with matter. These pairs also diffuse in the cloud and produce non-thermal radiation by synchrotron process. The injected power in protons by the bowshock is a fraction of the kinetic power of the wind:

$$L_T \sim \frac{1}{2} \dot{M}_w V_w^2, \quad (3)$$

where  $\dot{M}_w$  is the wind mass-loss rate and  $V_w^2$  is the wind terminal velocity.



**Figure 1.** Random ejection directions of the six runaway stars ejected at the centre of a spherical MC (not to scale).

Here we consider as a first approach a spherical young MC<sup>3</sup> of radius  $R_{MC} = 50$  pc and core radius  $R_n = 0.5$  pc. This cloud hosts a massive young stellar cluster. The density profile of the cloud is given by Eq. (1), with  $\beta = 1$  (*boxy cloud*) and  $n_0 = 10^4$   $cm^{-3}$ . The total mass of the cloud is  $M_{MC} \sim 10^6 M_\odot$ . We assume that the cluster ejects six massive stars in the last Myr. Additionally, we adopt in our simulations that all stars have been ejected at approximately the same time in random spatial directions, as illustrated in Fig. 1.

The ejection probability of a star is  $\propto V_*^{-\nu}$ , therefore it is more likely to eject stars of low velocity. We consider then three stars with velocity  $V_* \sim 30$  km  $s^{-1}$ , two stars of velocity  $V_* \sim 65$  km  $s^{-1}$ , and one of  $V_* \sim 100$  km  $s^{-1}$ . Also, runaway stars of spectral types O9 are more common than O4-type stars; then we consider one star of type O4I, three of type O9I and two intermediate cases; the maximum energies we estimate for locally accelerated protons are  $10^{14}$  eV,  $10^{12}$  eV and  $10^{13}$  eV, respectively<sup>4</sup>. These parameters are shown in Table 1. The stars inject protons continuously during 1 Myr. The maximum energies that protons reach do not depend on the medium density (see, del Valle & Romero 2014) and neither does the injected power, so these quantities are constant during the motion of the stars through the cloud.

### 4 PHYSICAL MODEL

As mentioned, we do not take into account the physical details of the injectors (the stellar bowshocks); we consider them as punctual, moving with constant velocity  $V_*$  through the cloud, without perturbing the density distribution. The

<sup>3</sup> MCs can be disrupted by the action of the winds and radiation of the new stars. Evolved MC are not expected to be spherical but annular; such a system will be considered elsewhere.

<sup>4</sup> These values are consistent with the maximum energies for protons obtained in del Valle & Romero (2014).

$\star \#$	$V_\star$ [km s $^{-1}$ ]	$\dot{M}_w$ [ $M_\odot$ yr $^{-1}$ ]	$V_w$ [km s $^{-1}$ ]	Power [erg s $^{-1}$ ]	Max. energy [TeV]	$\tau$ [Myr]
1	30	$10^{-4}$	2200	$3 \times 10^{35}$	100	1.6
2	30	$10^{-6}$	800	$4 \times 10^{32}$	1	1.6
3	30	$10^{-5}$	1000	$7 \times 10^{33}$	10	1.6
4	65	$10^{-5}$	1000	$7 \times 10^{33}$	10	0.7
5	65	$10^{-6}$	800	$4 \times 10^{32}$	1	0.7
6	100	$10^{-6}$	800	$4 \times 10^{32}$	1	0.5

**Table 1.** Wind velocity and mass-loss rate, stellar velocity, injected power, proton maximum energies and crossing time ( $\tau = R_{MC}/V_\star$ ) for each runaway star considered (see text).

relativistic protons diffuse into the cloud. Because of the linear nature of the problem, we solve the equations for each star and sum all contributions to obtain the final result.

The spectral energy distribution  $N_p$  of the protons follows the transport equation:

$$\frac{\partial N_p(\vec{r}, E, t)}{\partial t} = \vec{\nabla} \cdot [D(\vec{r}, E) \nabla N_p(\vec{r}, E, t)] - \frac{\partial}{\partial E} (P(\vec{r}, E) N_p(\vec{r}, E, t)) + Q_p(\vec{r}, E, t), \quad (4)$$

where  $D(\vec{r}, E)$  is the diffusion coefficient of the particles,  $P(\vec{r}, E) \equiv -(\mathrm{d}E/\mathrm{d}t)$  is the radiative energy loss rate and  $Q_p(\vec{r}, E, t)$  is the injection function. We adopt a scalar diffusion coefficient<sup>5</sup> that depends only on the particle energy  $D(\vec{r}, E) \equiv D(E)$ ; given the geometry of the scenario considered here, we adopt a spherical coordinate system  $(R, \theta, \phi)$ , with its origin at the cloud centre (see Fig. 1). During the calculation for each star (see details in §5), we adopt a coordinate system in which the star moves along the polar axis. Thus the proton density function  $N_p$  depends spatially only on  $R$  and  $\theta$ , i.e.  $N_p \equiv N_p(R, \theta, E, t)$ . In this coordinate system Eq. (4) becomes:

$$\frac{\partial N_p}{\partial t} = D(E) \left[ \frac{1}{R^2} \frac{\partial}{\partial R} \left( R^2 \frac{\partial N_p}{\partial R} \right) + \frac{1}{R^2 \sin \theta} \frac{\partial}{\partial \theta} \left( \sin \theta \frac{\partial N_p}{\partial \theta} \right) \right] - \frac{\partial}{\partial E} (P(R, \theta, E) N_p) + Q_p(R, \theta, E, t). \quad (5)$$

The dominant losses for protons are  $p-p$  inelastic collisions, while the ionization losses are negligible in the range of energies considered (Aharonian & Atoyan 1996). The loss term is  $P(R, \theta, E) = E (n(R) c \kappa_{pp} \sigma_{pp})$  where  $\kappa_{pp}$  is the inelasticity ( $\sim 0.45$ ) and  $\sigma_{pp}$  is the cross section for inelastic collisions. The dependence on  $R$  and  $\theta$  of the radiative losses is given through the density – see Eq. (1) –.

The  $\sigma_{pp}$  cross section can be approximated by (Kelner, Aharonian & Bugayov 2006):

$$\sigma_{pp} = (34.3 + 1.88L + 0.25L^2) \left[ 1 - \left( \frac{E_{\mathrm{th}}}{E_p} \right)^4 \right]^2 \mathrm{mb}, \quad (6)$$

where  $L = \ln(E_p/1\mathrm{TeV})$  and  $E_{\mathrm{th}} = 1.22 \mathrm{GeV}$ .

The injection function  $Q_p$  is:

$$Q_p(R, \theta, E, t) = N_0 E^{-2} \delta^3(\vec{r} - \vec{r}_\star), \quad (7)$$

<sup>5</sup> In its more general form, the diffusion coefficient is a tensor (e.g., Berezhinskii et al. 1990).

where  $\vec{r}_\star = \vec{V}_\star t$  is the position of each star with respect to the cloud centre;  $N_0$  is the normalization constant which depends on the injected power in relativistic particles for each star, as discussed above. We only consider proton injection when the stars are inside the cloud (i.e.  $t \leq \tau$ ).

The spectral energy distribution of secondary pairs  $N_{e\pm}$  obeys the same transport equation as protons (Eq. (5)), but the radiative term  $P(R, \theta, E)$  and the injection function  $Q_{e\pm}(R, \theta, E, t)$  are different. The pairs are injected through the decay of charged pions produced in the  $p-p$  collisions (e.g., Orellana et al. 2007). The injection of leptons can be calculated from (Kelner, Aharonian & Bugayov 2006):

$$Q_{e\pm}(R, \theta, E, t) = \int_{E_{e\pm}}^{\infty} \sigma_{pp}(E_p) n(R) c N_p(R, \theta, E_p, t) \times F(E_{e\pm}, E_p) \frac{\mathrm{d}E_p}{E_p}, \quad (8)$$

where  $F(E_{e\pm}, E_p)$  is the electron spectrum of the decay  $\pi \rightarrow \mu + \nu_\mu$ .

The relevant losses for pairs are synchrotron radiation and relativistic Bremsstrahlung (see, for example, Aharonian 2004 and references therein).

#### 4.1 Diffusion

The diffusion coefficient is a key parameter in the study of the diffusion of energetic particles. It is a poorly determined quantity, from both the observational and theoretical point of view. The theoretical determination of the diffusion coefficient is a very complex task (e.g., Yan & Lazarian 2004, 2008) and observations are necessary to constraint the models. Cosmic-ray diffusion is a non-linear process in which the CRs generate the instabilities that produce the turbulence they interact with (e.g., Nava & Gabici 2013, and references therein). Near the particle accelerators, where the population of CRs is very high, the diffusion coefficient can significantly decrease through instabilities (Ptuskin, Zirakashvili & Plesser 2008; Malkov et al. 2013; Yan & Lazarian 2011). Furthermore, slow diffusion is expected in dense regions (e.g., Ormes, Ozel & Morris 1988).

Through gamma-ray observations of the SNR W28 – a remnant on its radiative phase, localized in a region of dense molecular gas – illuminating a MC, a significant suppression of the diffusion coefficient with respect to the averaged galactic values was reported (e.g., Gabici 2011). Also,

Yan, Lazarian & Schlickeiser (2012) using a self-consistent model for the acceleration of CRs and the gamma-ray production in W28, required a high suppression of the ISM diffusion coefficient to match the gamma observations. In these studies isotropic diffusion was considered. If the isotropic assumption is dropped, the conclusions are different. Under some physical conditions diffusion becomes anisotropic, particles diffuse preferentially parallel to the magnetic field lines (e.g., Casse, Lemoine & Pelletier 2002). An anisotropic treatment was developed in Nava & Gabici (2013), where the diffusion coefficient is not suppressed to fit the observations. Both scenarios fit the observations of the SNR W28, showing that a great uncertainty exists on the diffusion coefficient.

Here we adopt a phenomenological approach similar to the one used in Gabici, Aharonian & Blasi (2007). The diffusion coefficient is a power law in the particle energy:

$$D(E) = \chi D_{10} \left( \frac{E}{10 \text{ GeV}} \right)^\delta, \quad (9)$$

where  $D_{10}$  is the value of  $D$  at  $E = 10$  GeV. The power  $\delta$  varies between 0.3 – 0.6 depending on the power-law spectrum of the turbulence of the magnetic field. The parameter  $\chi < 1$  takes into account the suppression of the diffusion coefficient inside the turbulent medium of the cloud. For  $\delta$  and  $D_{10}$  we take values considered as typical in the Galaxy 0.5, and  $10^{27} \text{ cm}^2 \text{ s}^{-1}$ , respectively (Berezinskii et al. 1990). We study two cases of  $\chi$ :  $10^{-1}$  – expected in dense regions – and  $10^{-3}$  – an extreme case –. As we are considering an isotropic diffusion coefficient, no specification of the magnetic field direction is required in our calculations.

## 4.2 Cosmic-ray sea

In order to compare the contribution of the injected protons with the cosmic-ray background of the Galaxy we calculate the cosmic-ray flux expected in the cloud, following Gabici, Aharonian & Blasi (2007). CRs do not freely penetrate the cloud; they diffuse slowly, especially in dense regions. To get the cosmic-ray distributions  $N_p^{\text{CR}}$  consistently with the parameters adopted, we solve the transport equation in steady state. This means, Eq. (5) with  $\partial/\partial t = 0$ , null injection function and the condition that the distribution  $N_p^{\text{CR}}$  at the edges of the cloud match the cosmic-ray sea distribution. We consider only protons because it is the dominant cosmic-ray component. We also consider the secondary pairs that the high-energy protons produce in their collisions with the cold protons. We take the galactic cosmic-ray-flux equal to the locally observed one<sup>6</sup> (e.g., Simpson 1983):

$$J_{\text{CR}}^{\text{gal}}(E) = 2.2 \left( \frac{E}{\text{GeV}} \right)^{-2.75} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ GeV}^{-1}. \quad (10)$$

We also consider the case in which the background cosmic-ray flux is one order of magnitude less than the locally observed flux, given by the latter equation.

## 4.3 Emission

We calculate the  $p - p$  emissivity for protons and the synchrotron emission produced by the secondary pairs. In the ISM the luminosity produced by inverse Compton scattering is in general negligible compared to the  $p - p$  contribution (see, Bosch-Ramon, Aharonian & Paredes 2005). Relativistic Bremsstrahlung is significant only at energies smaller than 1 GeV (Aharonian 2004; Gabici, Aharonian & Blasi 2007) and here we neglect it. In what follows we describe the numerical methods used.

## 5 NUMERICAL METHODS

The transport equation is solved for a single cosmic-ray injector at a time. We consider the star moving along the polar axis of an spherical system of coordinates. In this way, the system has azimuthal symmetry, allowing a reduction of the dimensionality of the problem. The coordinates of the particle distributions resulting from each injector star are then rotated (by randomly chosen angles, shown in Fig. 1) and interpolated into a 3D spatial grid. In this way the resulting distribution of particles is obtained by summing the contribution coming from each star. Below, we describe the numerical methods employed for solving the problem for one injector.

We evolve the transport equations for protons and pairs simultaneously (throughout this section  $N$  represents the distribution of protons or pairs, without distinction) in a discrete grid of the phase space  $(E, R, \theta) \in [1 \text{ MeV}, 100 \text{ TeV}] \times [0, 50 \text{ pc}] \times [0, \pi]$ , using the finite-volumes method. The phase space is therefore divided in a grid of cells with central values  $E_l, R_i, \theta_j$  ( $1 \leq l \leq L$ ,  $1 \leq i \leq M$ , and  $1 \leq j \leq K$ ). The lengths of the cells  $(E_l, R_i, \theta_j)$  are given by  $\Delta E_l = E_{l+1/2} - E_{l-1/2}$ ,  $\Delta R_i = R_{i+1/2} - R_{i-1/2}$ ,  $\Delta \theta_j = \theta_{j+1/2} - \theta_{j-1/2}$ , where  $\alpha \pm 1/2$  ( $\alpha = l, i, j$ ) are the values at the left/right interface of the cell. The energy grid  $(E_l, 1 \leq l \leq L)$  is logarithmically spaced, while the radial  $(R_i, 1 \leq i \leq M)$  and polar  $(\theta_j, 1 \leq j \leq K)$  grids are uniformly spaced. In the simulations presented in this work, we employ the grid resolution  $(L, M, K) = (128, 64, 64)$ .<sup>7</sup>

The density of particles at a given time  $t$  is represented inside each cell by the average value  $N_{l,i,j}(t) \equiv N(E_l, R_i, \theta_j, t)$ , i.e., the number of particles inside the discrete volume of the phase space  $\Delta E_l \Delta R_i \Delta \theta_j$  at a time  $t$  is given by:  $N_{l,i,j}(t) \Delta E_l \Delta R_i \Delta \theta_j$ , where  $\Delta V_{i,j} \approx 2\pi R_i^2 \Delta R_i \sin \theta_j \Delta \theta_j$ .

At  $t = 0$  we consider  $N_{l,i,j}(t = 0) = 0$  for protons and pairs (i.e., no particles)<sup>8</sup>.

<sup>7</sup> When solving the distribution of particles for the galactic CR background, we extend the energy range to  $[1 \text{ MeV}, 10^3 \text{ TeV}]$ . Because of radial symmetry, the grid resolution employed is  $(L, M, K) = (144, 64, 1)$ .

<sup>8</sup> In order to obtain numerically the steady state solution for the distribution of the background CRs, we consider  $N_{\text{CR},l,j,k}(t = 0) = 0$  inside the molecular cloud, and we evolve the transport equation during enough time for the solution to become time independent.

<sup>6</sup> However, this assumption is *ad hoc*, see the discussion in Sec. 7.

The energy boundary conditions we impose to  $N$  are

$$N(E < 1 \text{ MeV}, R, \theta, t) = N(E > 100 \text{ TeV}, R, \theta, t) = 0, \quad (11)$$

i.e., no particles outside the energy bounds. In fact, these limits do not influence the system evolution, because the upper limit is above the maximum energy of the injected protons, at the same time that the advection in the energy space is always directed to smaller energies. The lower bound is physically fixed because relativistic particles have kinetic energies greater or of the order of their rest mass. The spatial boundary conditions are

$$N(E, R > 50 \text{ pc}, \theta, t) = 0, \quad (12)$$

i.e., no particles outside the MC, and

$$\frac{\partial N(E, R, \theta = 0, t)}{\partial \theta} = \frac{\partial N(E, R, \theta = \pi, t)}{\partial \theta} = 0, \quad (13)$$

due to the azimuthal symmetry.

For the calculation of the CR background distribution (see Sec. 4.2) the following boundary conditions are used instead:

$$N_{CR}(E > 10^3 \text{ TeV}, R, \theta, t) = 0, \quad (14)$$

and

$$N_{CR}(E, R > 50 \text{ pc}, \theta, t) = \frac{4\pi}{c} J_{CR} \left( \frac{E}{1 \text{ GeV}} \right)^{-\alpha}, \quad (15)$$

where the last condition is valid only for protons, and  $J_{CR}$  is the CR flux at  $E = 1 \text{ GeV}$ . The other boundary conditions are identical to the ones described before. Here we should remark that the upper boundary in the energy space affects the solution because, differently from the protons injected from the stars, there is no established cut-off at the cosmic-ray highest energies. We keep the energy range broader enough to minimize these effects.

The numerical integration of the transport equation is performed using the operator splitting method, in the way described below. Each time-step integration evolves the particle density distribution on the grid  $N_{l,i,j}^n \equiv N_{l,i,j}(t^n)$  from time  $t^n$  to time  $t^{n+1} = t^n + \Delta t$ , through three sub-steps described below.

Firstly, we integrate only the losses term of the transport equation,

$$\frac{\partial N(E, R, \theta, t)}{\partial t} = -\frac{\partial}{\partial E} [F(E, N(E, R, \theta, t))], \quad (16)$$

where the flux  $F(E, N(E, R, \theta, t)) \equiv P(E)N(E, R, \theta, t)$  is an advection in the energy space. In the finite-volume formulation, we employed an upwind scheme of second order<sup>9</sup> for calculating the fluxes at the interface of the cells. The intermediate solution  $N_{l,i,j}^{n+1/3}$  is then obtained from the solution  $N_{l,i,j}^n$  at time  $t^n$  through the explicit Euler method:

$$\frac{N_{l,i,j}^{n+1/3} - N_{l,i,j}^n}{\Delta t} = -\frac{1}{\Delta E_l} (F_{l+1/2,i,j}^n - F_{l-1/2,i,j}^n). \quad (17)$$

Here  $F_{l\pm 1/2,i,j}^n$  represents the numerical fluxes at the cell interfaces.

Secondly, we integrate only the diffusion part of the transport equation,

$$\frac{\partial N}{\partial t} = D(E) \left[ \frac{1}{R^2} \frac{\partial}{\partial R} \left( R^2 \frac{\partial N}{\partial R} \right) + \frac{1}{R^2 \sin \theta} \frac{\partial}{\partial \theta} \left( \sin \theta \frac{\partial N}{\partial \theta} \right) \right]. \quad (18)$$

For solving such integration, we use the semi-implicit Crank-Nicolson method, with the gradients calculated at the cell interfaces, using central differences. This scheme is, therefore, second order accurate. We then get a second intermediate solution,  $N_{l,i,j}^{n+2/3}$  from the solution  $N_{l,i,j}^{n+1/3}$ :

$$\frac{N_{l,j,k}^{n+2/3} - N_{l,j,k}^{n+1/3}}{\Delta t} = \frac{1}{2} D(E) \left[ L(N_{l,i,j}^{n+2/3}) + L(N_{l,i,j}^{n+1/3}) \right], \quad (19)$$

with

$$L(N_{l,i,j,k}) = \frac{1}{\Delta V_{i,j}} \left\{ \Delta S_{i+1/2,j} \frac{N_{i+1,j} - N_{i,j}}{\Delta R} - \Delta S_{i-1/2,j} \frac{N_{i,j} - N_{i-1,j}}{\Delta R} + \Delta S_{i,j+1/2} \frac{N_{i,j+1} - N_{i,j}}{R_i \Delta \theta} - \Delta S_{i,j-1/2} \frac{N_{i,j} - N_{i,j-1}}{R_i \Delta \theta} \right\}, \quad (20)$$

where  $\Delta S_{i\pm 1/2,j}$  and  $\Delta S_{i,j\pm 1/2}$  are the cell surfaces at the interfaces indicated by the indices. Our algorithm first tries to solve the linear system implied by Eqs. (19) and (20) using the iterative Krylov Space scheme GMRESR (Van der Vorst & Vuik 1994); when it fails to converge to the solution (with relative residue  $< 10^{-7}$  in the 2-norm), it employs our implementation of a Multigrid solver.

Finally, we add the contributions due to the injection using the Euler explicit method:

$$\frac{N_{l,i,j}^{n+1} - N_{l,i,j}^{n+2/3}}{\Delta t} = Q_{l,i,j}^{n+2/3}. \quad (21)$$

Then, the final solution  $N_{l,i,j}^{n+1}$  at  $t^{n+1}$  is obtained.

The time-steps  $\Delta t$  are chosen in accordance with the Courant-Friedrichs-Lewy stability criterion for the minimum time step of the advection equation ( $\delta t_{\text{adv}}$ , Eq. 17) and of the diffusion equation ( $\delta t_{\text{dif}}$ , Eq. 18). We also impose the condition that the time step must be smaller than the time it takes the star to cross one cell ( $\delta t_{\text{inj}}$ ). These three time-steps constraints are calculated with the following formulae:

$$\delta t_{\text{adv}} = \min \left\{ \frac{\Delta E_l}{P(E_l, R_i, \theta_j)} \right\}, \quad (22)$$

$$\delta t_{\text{dif}} = \min \left\{ \frac{\Delta \theta (\Delta R)^2}{D(E_l)} \right\}, \quad (23)$$

$$\delta t_{\text{inj}} = \frac{\Delta R}{V_*}. \quad (24)$$

The minimum is taken over all the grid values. The time-step is then  $\delta t = \min \{ \epsilon_{\text{adv}} \delta t_{\text{adv}}, \epsilon_{\text{dif}} \delta t_{\text{dif}}, \epsilon_{\text{inj}} \delta t_{\text{inj}} \}$ . We use the safety factors  $\epsilon_{\text{adv}} = 0.5$ ,  $\epsilon_{\text{inj}} = 0.5$ . As the semi-implicit method used for the diffusion equation is unconditionally stable, we use  $\epsilon_{\text{dif}} = 10$ .

We checked the convergence of the solutions presented below performing additional runs (not shown) of some of the models using different resolutions (lower and higher). In addition, we also performed several tests changing the order of the operators sequence (advection, diffusion, injection),

<sup>9</sup> We use the Piecewise Linear Method (PLM) with the Monotonic Central limiter, which is second order accurate on a uniform grid.

and we have not found significant difference between the results.

## 6 RESULTS

### 6.1 Particle distributions

In what follows we show series of maps of the protons and  $e^\pm$  pairs distributions at a fixed energy and different times, adding the contributions of the six stars. The 2D maps are constructed integrating the 3D data along an arbitrary line of sight, chosen to be on the  $z$  direction (see Fig. 1).

In Figs. 2 and 3 we show the evolution maps of the proton distribution, for two energies: 10 GeV and 10 TeV, for  $\chi = 10^{-1}$  and  $\chi = 10^{-3}$ , respectively (i.e., fast and slow diffusion). The most energetic particles diffuse faster because of the power-law dependence of  $D(E)$  with energy. The different stars can be identified in the maps during the evolution; particularly the stars #6 and #4 are seen while they abandon the core region of the cloud. The most energetic star, #1, produces an important anisotropy in the particle distribution.

The Fig. 4 shows the evolution maps of the pairs created in the  $p-p$  interactions. Maps correspond to two energies: 10 GeV and 1 TeV, for the case  $\chi = 10^{-1}$ . The pair density is higher in the densest regions of the cloud; in the core also the synchrotron losses are much more intense.

### 6.2 Emissivity

We calculate the synchrotron emissivity produced by the interaction of the secondary pairs with the inhomogeneous magnetic field given by Eq. (2). We also compute the emissivity produced in the  $p-p$  collisions by neutral pion decays; the target density is  $n(R)$ , the density of the MC mass, see Eq. (1). The corresponding formulae can be found in, e.g., Aharonian (2004) and references there in. Figures 5 and 6 show the evolution of the gamma emissivity for  $E = 10$  GeV, for both diffusion scenarios considered here respectively. The emission is highly anisotropic and its intensity follows the injectors motion. This is more clear in the case of slow diffusion. The maximum emissivity is reached immediately after the ejection of the stars, while the high-energy particles are concentrated in the high density (and high magnetic field intensity) MC core.

Pairs are created with high energies and they produce synchrotron radiation from radio to X-rays. In the maps displayed in Fig. 7 we show the evolution of the synchrotron emissivity projected along the line of sight, for  $E = 1$  keV (soft X-rays) and  $\chi = 10^{-1}$ . Here we sum the contributions of all stars, but not all of them produce pairs that emit synchrotron radiation up to this energy. Because of the dependence of this emission with the magnetic field ( $\propto B^2$ ), the radiation is considerably more intense in the centre of the cloud, where  $B$  is higher.

### 6.3 Spectral energy distributions

Figure 8 shows the evolution of the total SEDs – integrated over a sphere of radius  $R_{MC} = 50$  pc – and the nuclear SED – integrated inside a sphere of radius  $r = 1.5$  pc –,

for  $\chi = 10^{-1}$ . The luminosity produced by the cosmic-ray background is also shown.

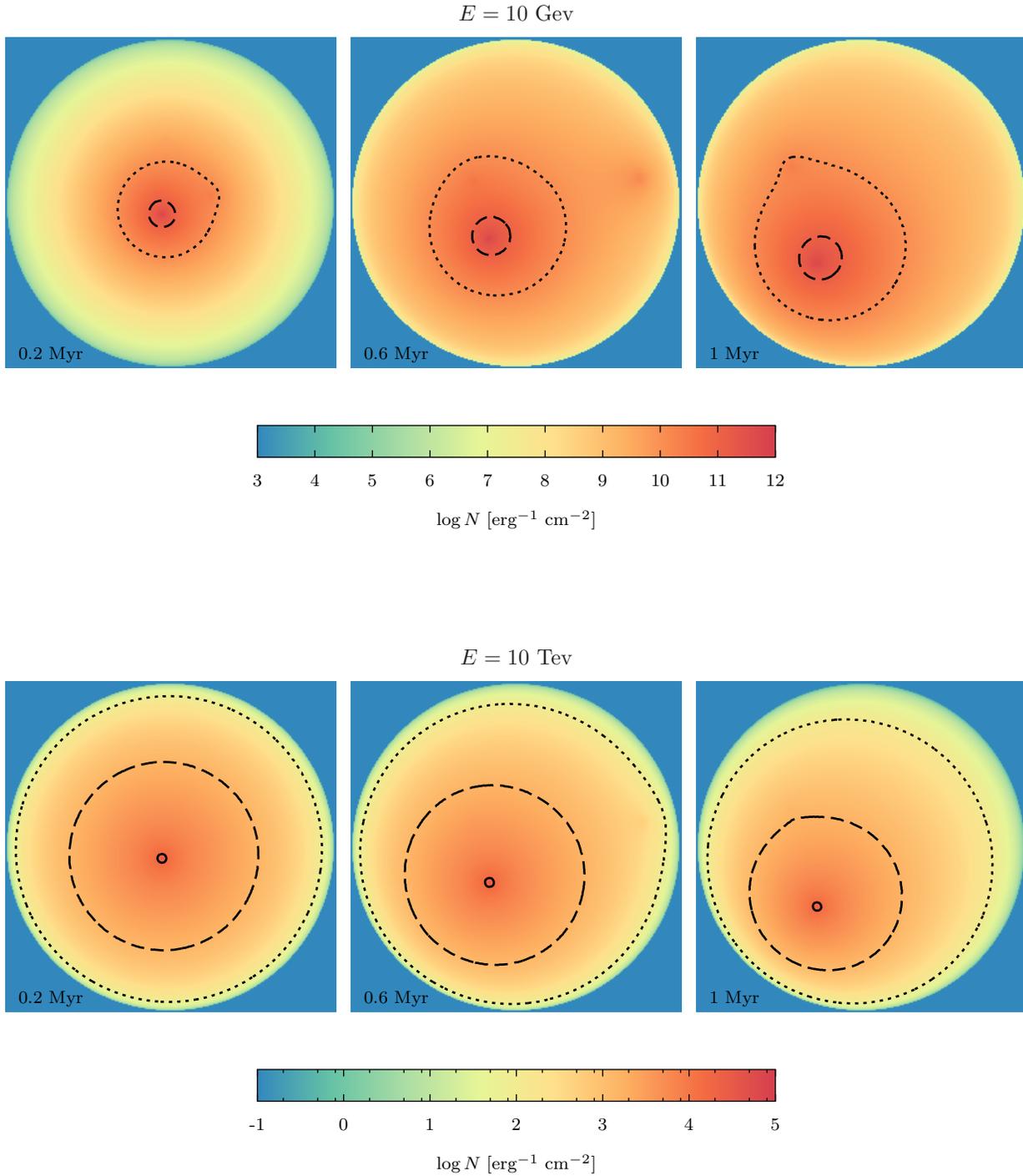
The gamma emission and the synchrotron radiation produced by stars #2-#6 are negligible in the total SED, for both cosmic-ray backgrounds. The contribution of star #1 dominates the spectrum over the luminosity produced by the CRs (dark-grey line in the SEDs) in the energy ranges  $10^{-3}$  eV to 1 keV and 100 GeV to 10 TeV. If the background of CRs is the lowest case consider here (light-grey line in the SEDs), star #1 dominates the SED in the energy ranges  $10^{-5}$  eV - 10 keV and 1 MeV - 10 TeV.

In the case of the nuclear SED the non-thermal emission produced by star #1 dominates over the background emission. The emission from the star #3 exceeds the background when the star is near the centre in the energy ranges  $10^{-3}$  eV - 10 eV and 1 MeV - 1 TeV. If the cosmic-ray density is lower, the emission produced by the weaker stars (#2, #3 and #4) exceeds the background at radio wavelengths and at energies  $\sim$  MeV, when the injection starts. In this case the contribution of the star #3 is greater than the background during a longer time, until  $\sim 0.7$  Myr.

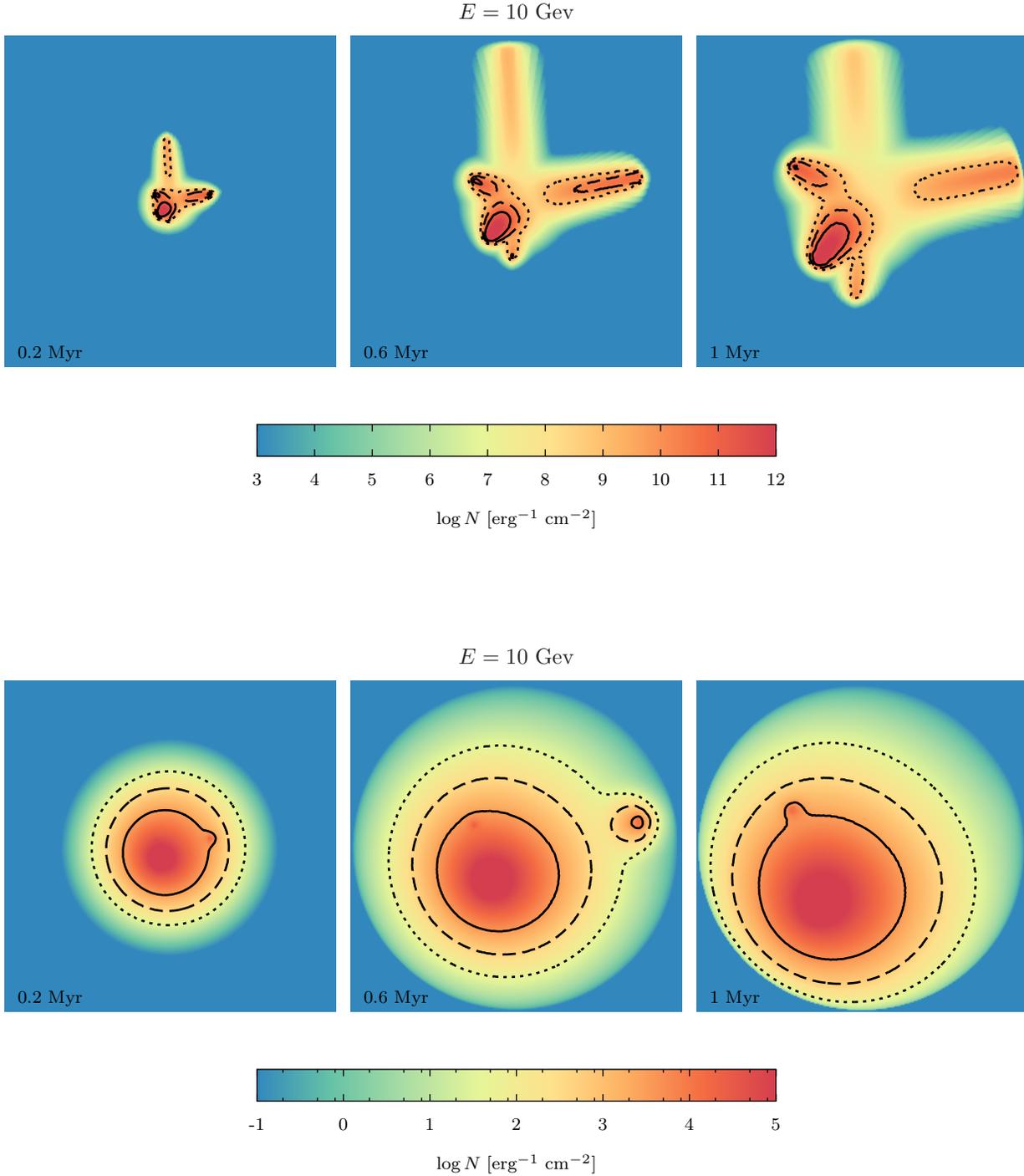
Figure 9 shows the evolutions of the total and nuclear SEDs for the case  $\chi = 10^{-3}$  (slow diffusion). In this case the total SED is dominated by the contribution of star #1, from radio to hard X-rays, and energies from  $\sim$  MeV to 10 TeV, during all the integration time. If the level of CRs is the lowest one considered here, stars #3 and #4 also exceed the background during all the integration time from the lowest energies up to  $10^2$  eV and from 1 MeV to 1 TeV. In the nuclear region the contribution of all stars exceeds the background (for both values of the CR level considered), when the stars are near the core. The stars #3 and #4 in the range of energies from MeV to GeV and TeV, respectively, overcome the cosmic-ray contribution even at the final integration time (1 Myr). The slow diffusion makes the injected particles to stay longer inside the cloud, radiating in the denser regions; the CRs penetrate less in the cloud because the larger diffusion time makes the energy losses more efficient.

It should be observed that the electron-positron pairs produced by the background CRs are limited in energy due to our energy grid limit of  $10^3$  TeV for the CR protons. Changing the upper limit in the energy increases the number of high-energy pairs, and consequently increases the high-energy tail of the background synchrotron emission. However, the increase on the emission is small and occurs at photon energies greater than 1 keV, where the synchrotron emission from the stars decreases.

Finally, the evolution of the total energy in protons (left) and pairs (right) for  $\chi = 10^{-1}$  are shown in Fig. 10 (top). The total energy of protons and pairs for stars #1, #2 and #3 increases slowly with time. As the stars move away from the central region of the MC the energy losses diminish as  $n$  and  $B$  decrease. For stars #4, #5 and #6 the total energy drops with time for  $t \gtrsim \tau$  (see Table 1); this is because the injection stops when the star leaves the MC. The evolution of the total gamma (left) and synchrotron (right) luminosity, also for  $\chi = 10^{-1}$ , can be seen in Fig. 10 (bottom). Initially, the total gamma luminosity increases very fast for all stars. As the stars move away from the centre,  $n$  and  $B$  decrease. However, the gamma luminosity does not decrease for stars #1, #2 and #3. For the fastest stars (#4, #5 and



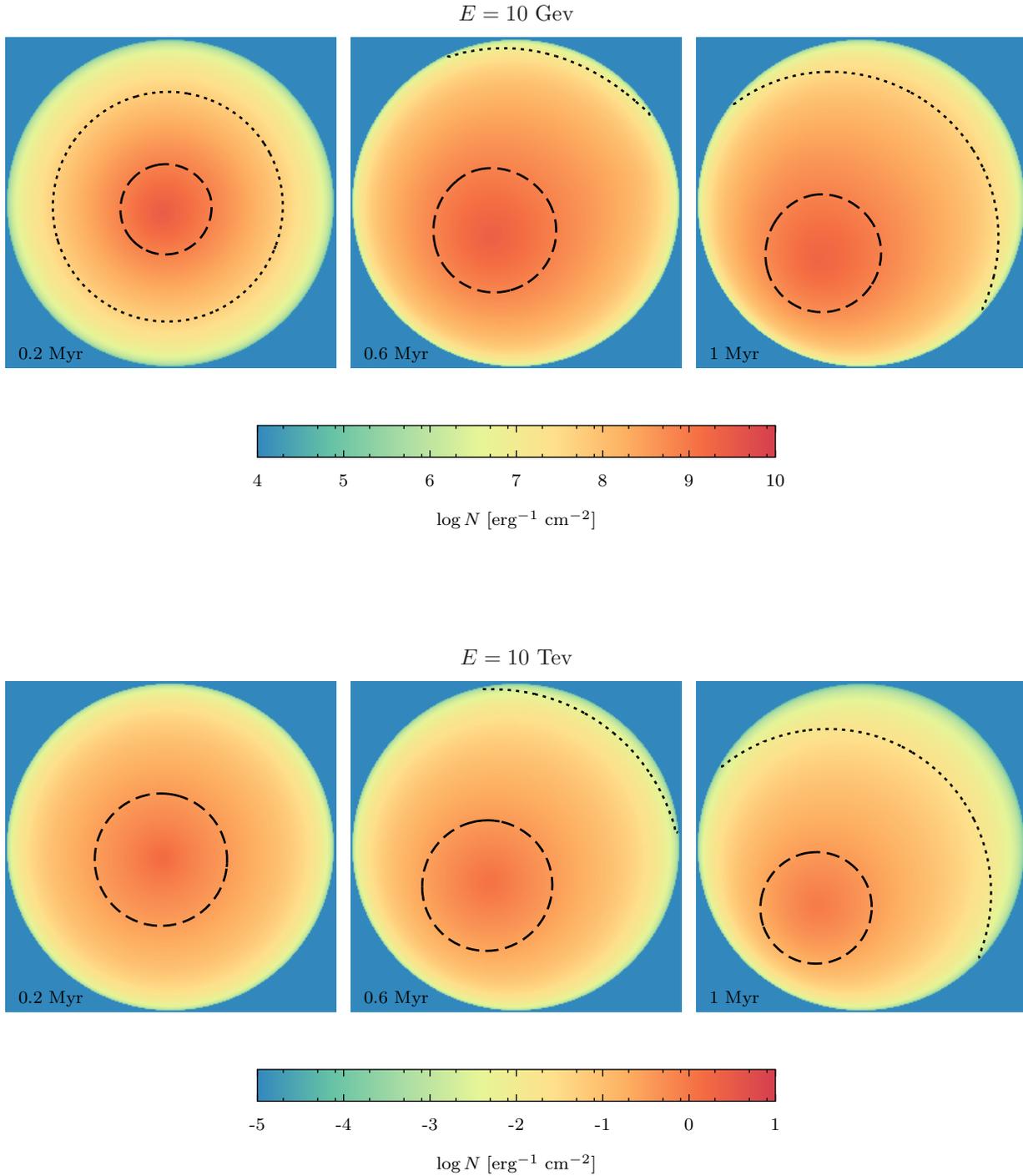
**Figure 2.** Proton distribution at fixed energy projected along the line of sight for the case  $\chi = 10^{-1}$ . Top:  $E_p = 10 \text{ GeV}$ ; bottom:  $E_p = 10 \text{ TeV}$ . Time evolves from left to right. The level curves correspond to 0.1 (dotted), 1 (dashed), and 10 (continuous) times the CR background distribution.



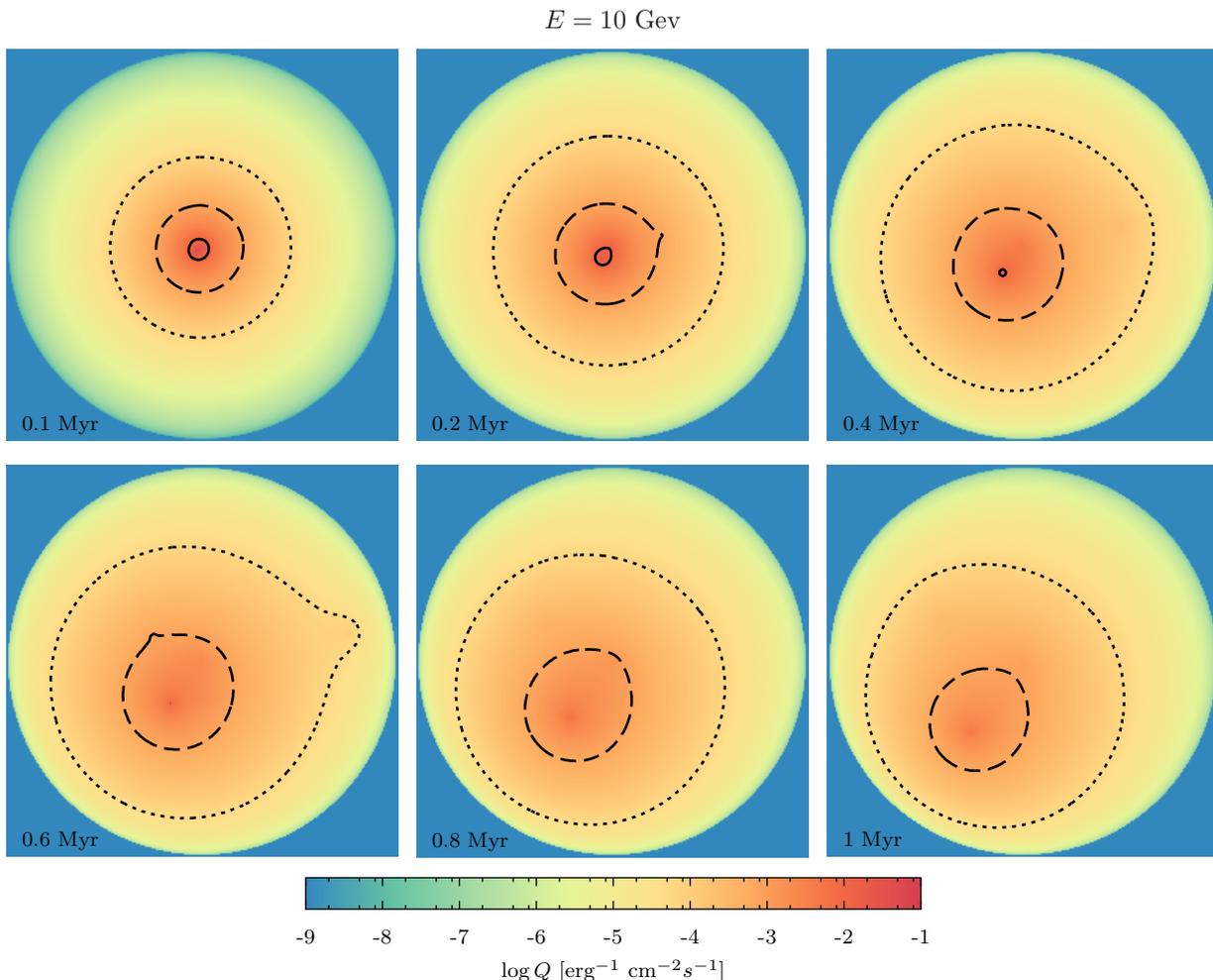
**Figure 3.** Same as the last figure, for  $\chi = 10^{-3}$ .

#6) the gamma luminosity decreases because they leave the MC during the integration time. The total synchrotron luminosity also increases very fast at the beginning, but after some time it starts to decrease for all stars; this might be

because  $B$  decreases faster than  $n$  with  $R$ , and due to the quadratic dependence of the synchrotron radiation with  $B$ .



**Figure 4.** Distribution of  $e^\pm$  pairs at fixed energy projected along the line of sight for the case  $\chi = 10^{-1}$ . Top:  $E_e = 10 \text{ GeV}$ ; bottom:  $E_e = 10 \text{ TeV}$ . Time evolves from left to right. The level curves correspond to 0.1 (dotted), and 1 (dashed) times the pairs background distribution.



**Figure 5.** Gamma-ray emissivity evolution, projected along the line of sight for  $\chi = 10^{-1}$ . The photon energy is  $E = 10 \text{ GeV}$ . Time evolves from top left to bottom right. The level curves represent 0.1 (dotted), 1 (dashed), and 10 (continuous) times the background emissivity.

## 7 DISCUSSION AND CONCLUSIONS

The locally injected protons and secondary pairs, under some assumptions, dominate over the cosmic-ray sea that penetrates the cloud. The gamma-ray luminosity produced by the protons reaches values of the same order as some of the detected luminosities in MCs, e.g.,  $\sim 10^{34} \text{ erg s}^{-1}$ .

A very energetic star, as the case of star #1, can inject a significant amount of protons in the medium and it is able to produce important gamma-ray emission over the whole cloud, overcoming the background emission produced by the cosmic-ray sea. This star dominates the gamma rays during most of the time in both cases considered here for the diffusion –  $\chi = 10^{-1}$  and  $\chi = 10^{-3}$  –. The contribution of the less powerful stars dominates locally over the cosmic-ray contribution. However, stars with weak winds, as stars #2, #5 and #6 do not inject enough power to overcome globally the emission produced by the cosmic-ray sea. The injected power we adopt here depends on the acceleration model of particles in bowshocks of runaway stars (del Valle & Romero 2012, 2014), so the actual injected power in specific sources could differ.

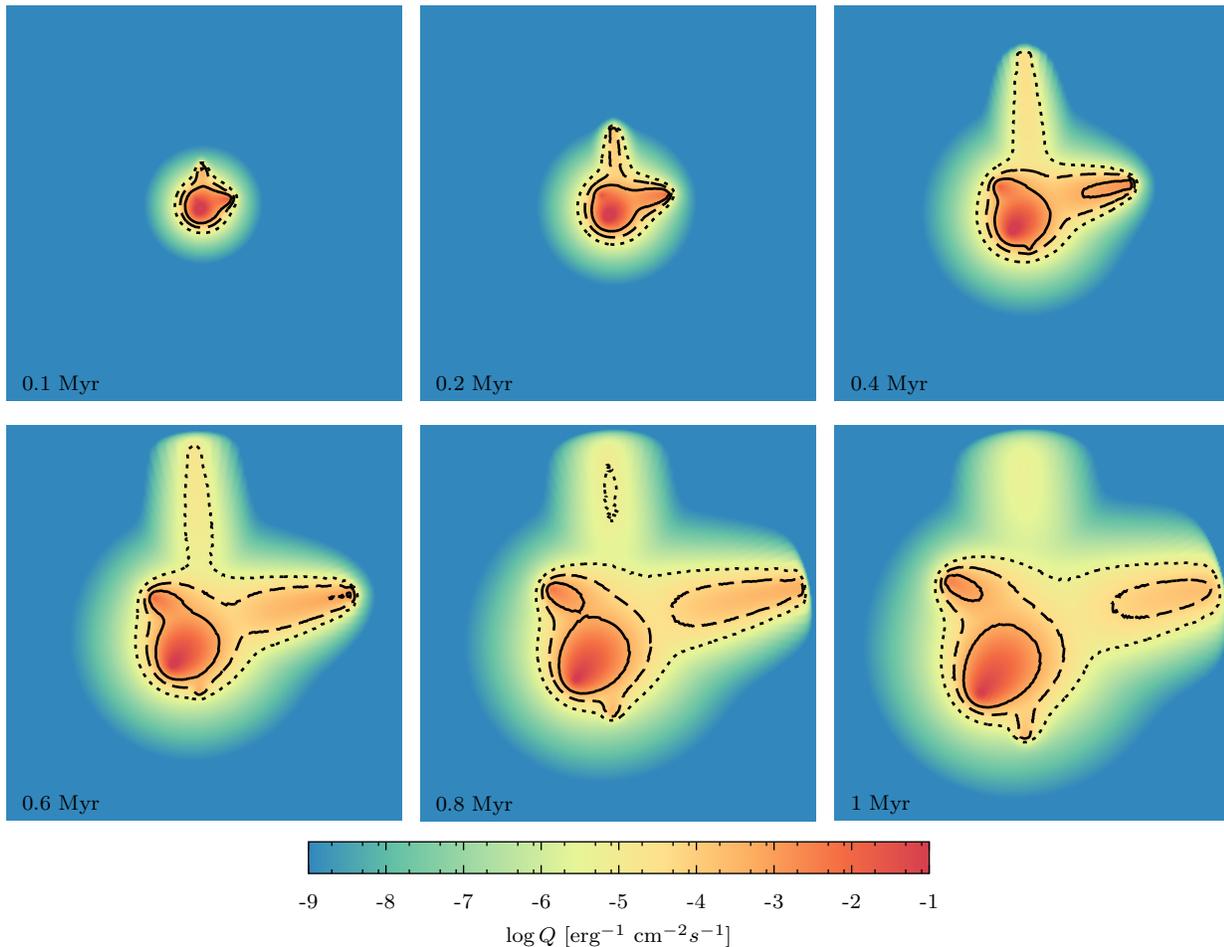
The non-thermal emission from radio to X-rays is significant, with luminosities of almost  $10^{32} \text{ erg s}^{-1}$ . However,

in a MC thermal radiation might dominate in many regions of this energy range. Additionally, the absorption produced by the MC matter is expected to be very intense from the IR to soft X-rays. Low radio frequencies are recommended, then, for the observational study of large clouds.

As can be inferred from the cases we present here, the results are very sensitive to particle diffusion and to the ambient cosmic-ray levels. Both quantities are not very well known. This fact makes the present research particularly valuable in the light of the inverse problem: detailed radio maps, including polarization, along with gamma-ray imaging might become a powerful tool to probe the physical conditions in the clouds.

The hypothesis that a uniform flux of CRs pervades the whole Galaxy can be inappropriate in some cases, especially at small spatial scales (Gabici 2013). The locally observed cosmic-ray flux might not represent the cosmic-ray population of the whole Galaxy. The local cosmic-ray flux as a matter of fact, could be contaminated by a few local sources. This assumption requires an observational confirmation, that might come from gamma-ray observations of nearby passive MCs (Aharonian 2004).

Regarding the diffusion coefficient, additional observa-

$E = 10 \text{ GeV}$ 

**Figure 6.** Same as Fig. 5 for slow diffusion ( $\chi = 10^{-3}$ ).

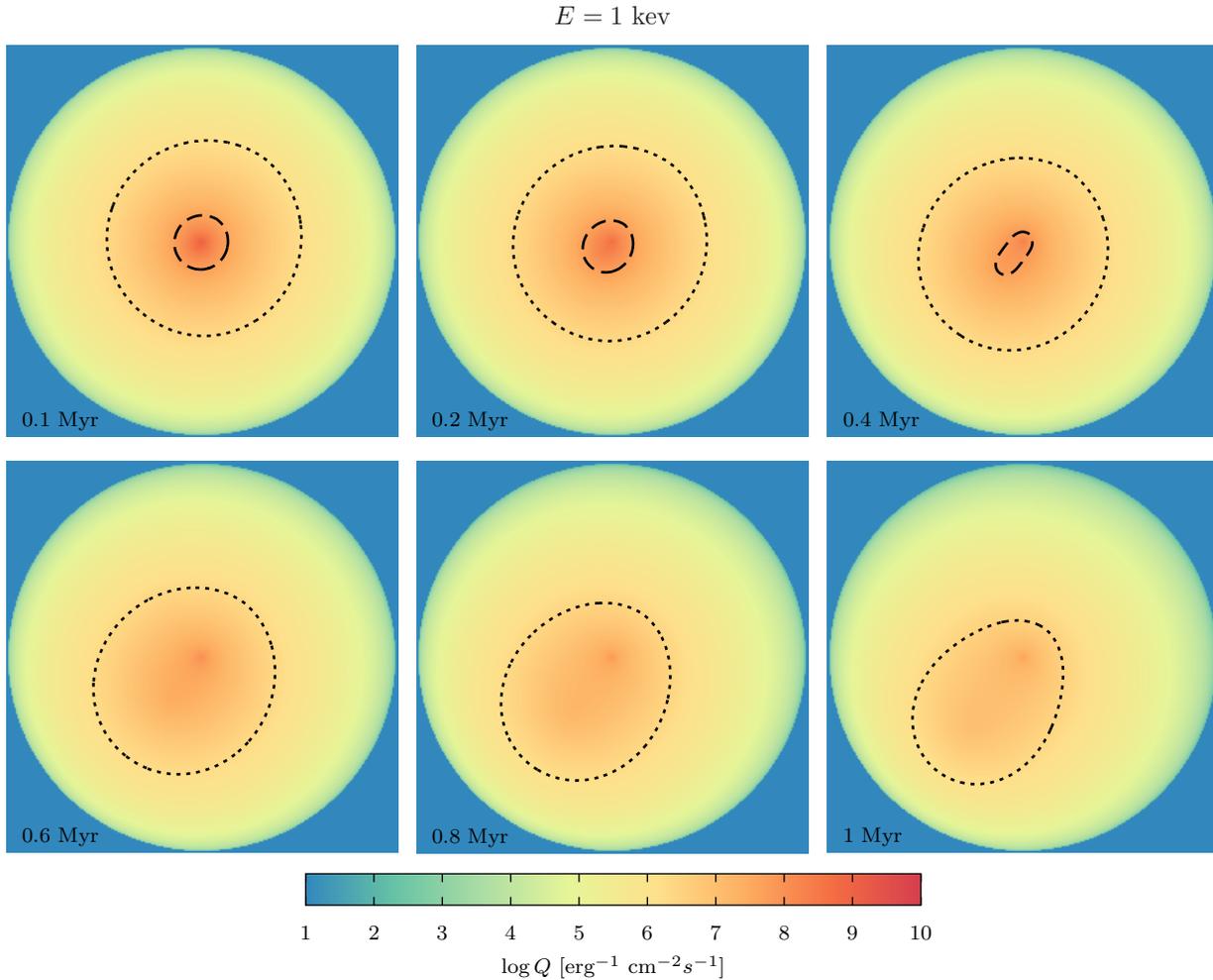
tions are necessary to obtain solid constraints. The forthcoming gamma-ray observatory CTA might play a fundamental role in this subject because of its great angular resolution and sensitivity (e.g., Gabici 2013; Pedalletti et al. 2013).

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**Figure 7.** Evolution of the synchrotron emissivity projected along the line of sight, for  $\chi = 10^{-1}$ . The photon energy is  $E = 1 \text{ keV}$ . Time evolves from top left to bottom right. The level curves represent 0.1 (dotted), 1 (dashed), and 10 (continuous) times the background emissivity.

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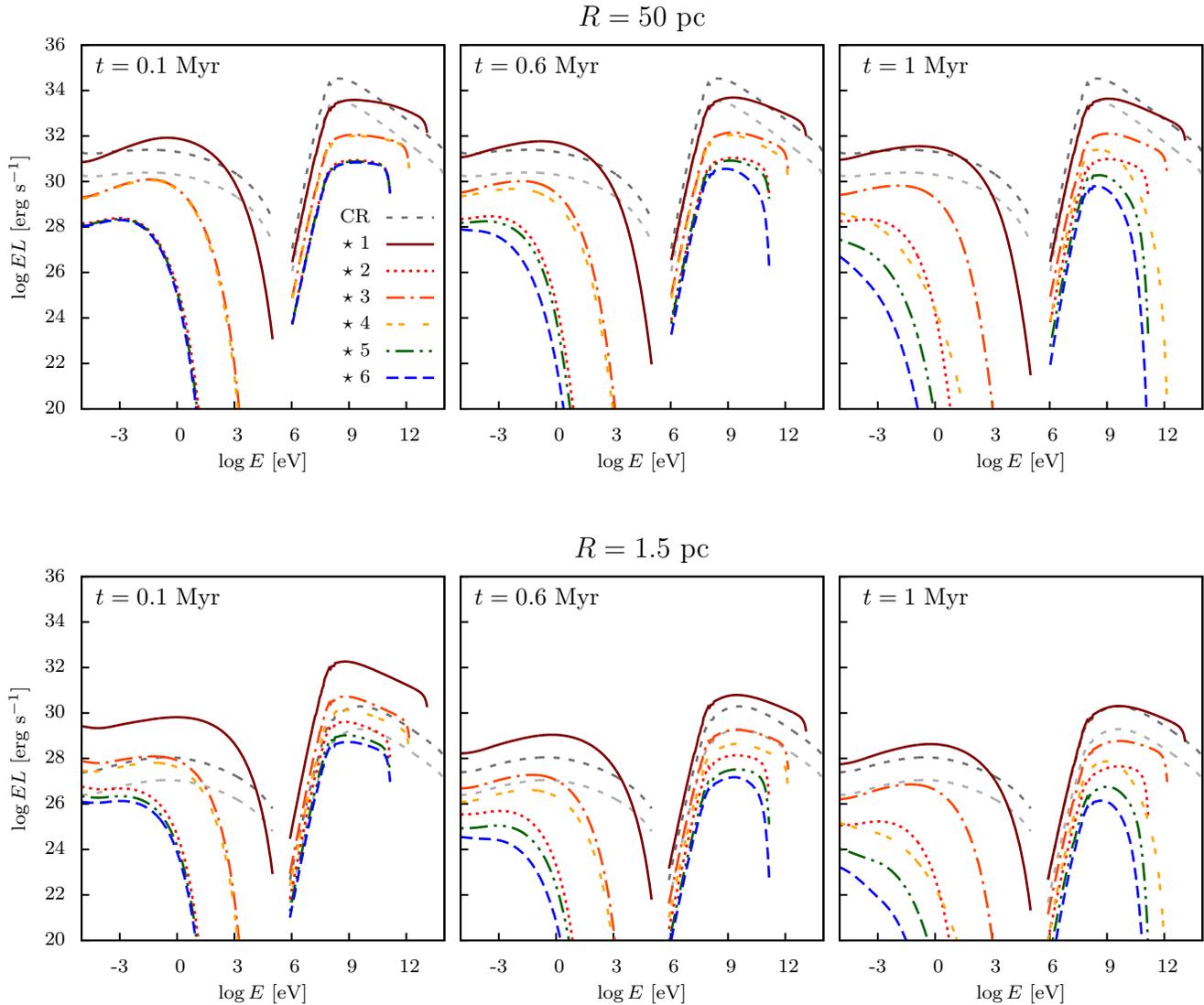
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**Figure 8.** Evolution of the total SED (top) and the nuclear SED (bottom) in the diffusion case  $\chi = 10^{-1}$ . The emission produced by the cosmic-ray background is indicated by “CR”. The light-grey line corresponds to the case in which the flux of CRs is lower than the flux observed locally. Time evolves from left to right.

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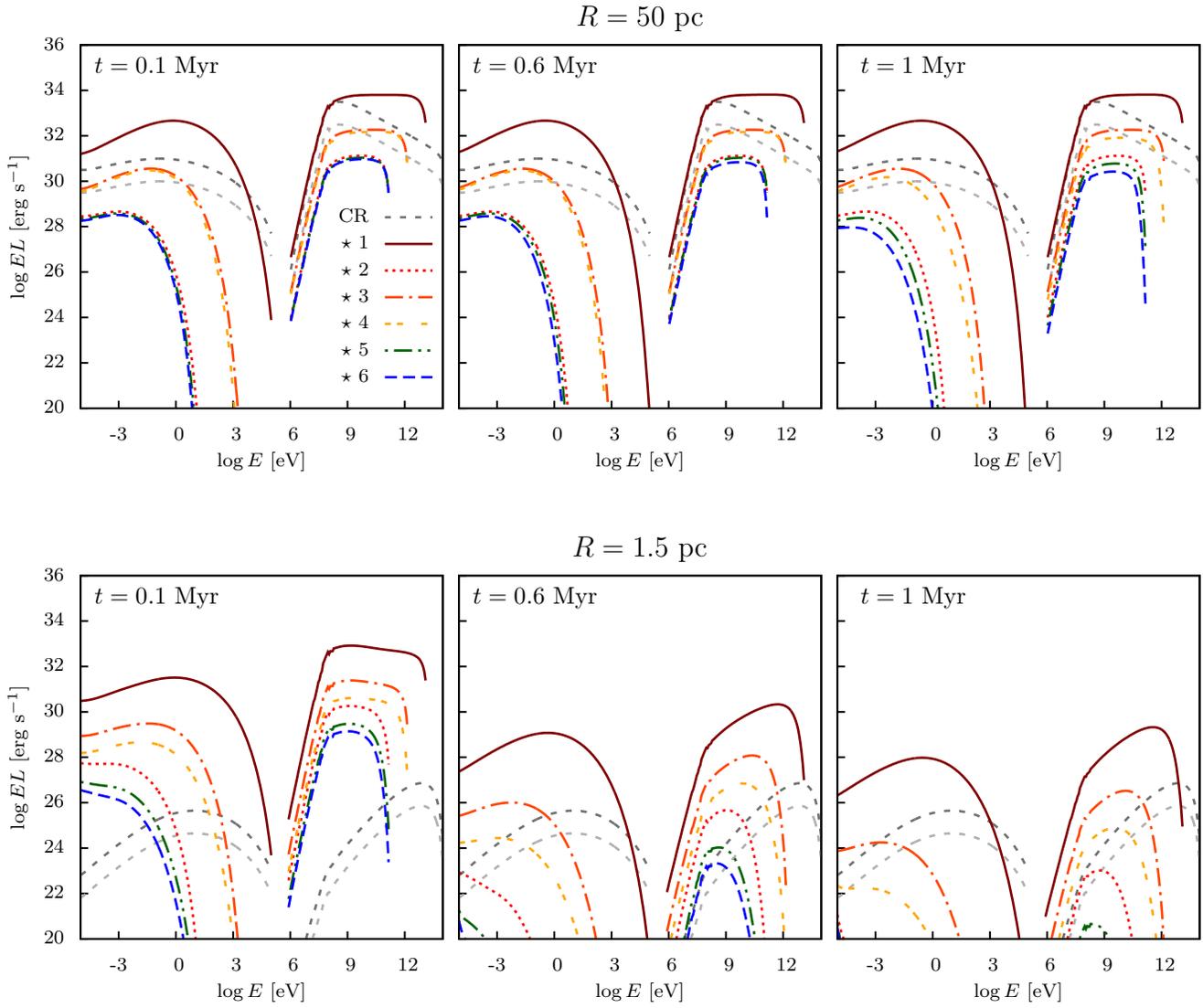
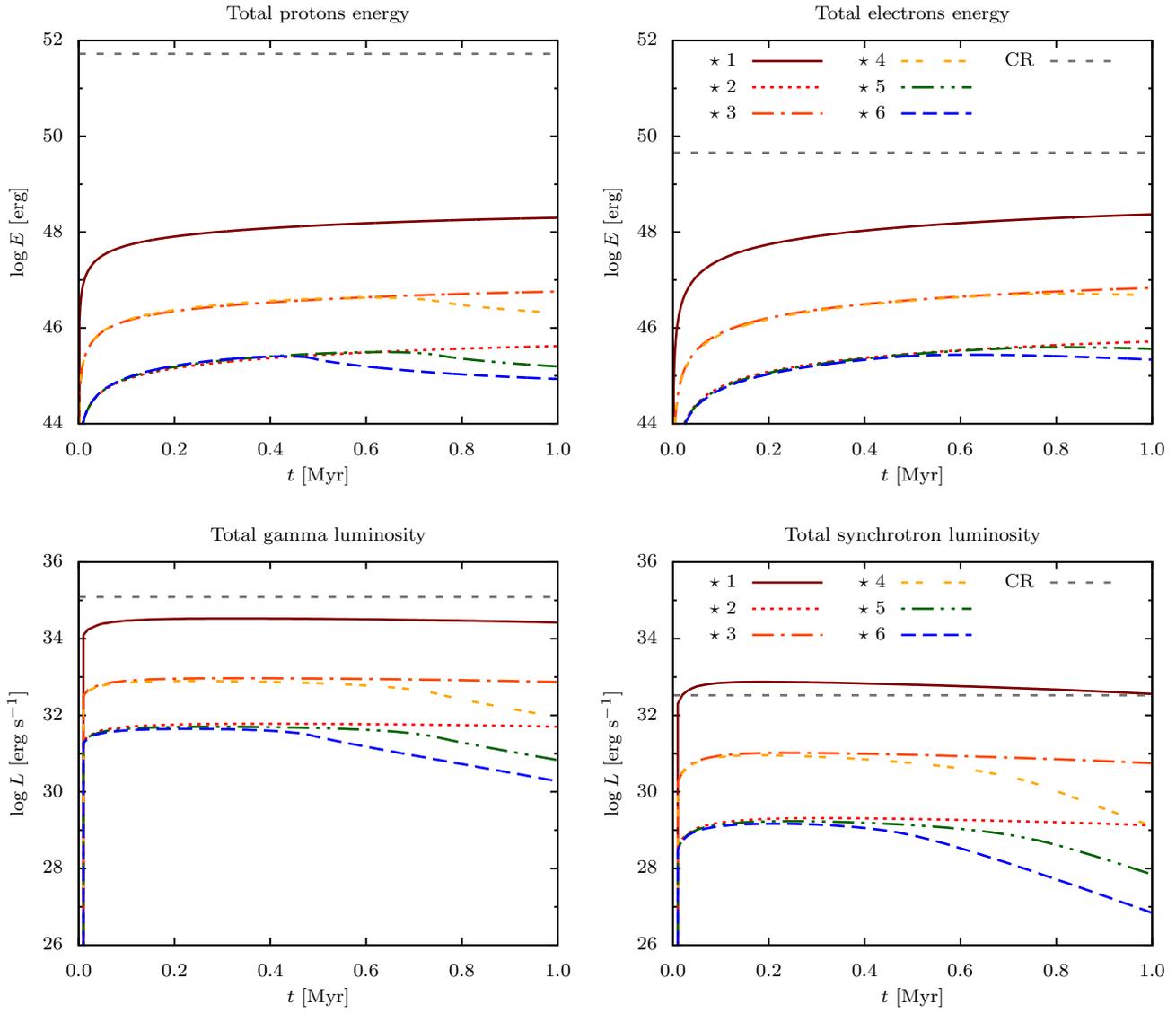


Figure 9. Same as Fig. 8 in the case  $\chi = 10^{-3}$ .



**Figure 10.** Top: evolution of total energy in protons (left) and pairs (right). Bottom: evolution of the total gamma (left) and synchrotron (right) luminosity. Here  $\chi = 10^{-1}$ .