Broad-band nonthermal emission from molecular clouds illuminated by cosmic rays from nearby supernova remnants

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ABSTRACT

Molecular clouds are expected to emit non-thermal radiation due to cosmic ray interactions in the dense magnetized gas. Such emission is amplified if a cloud is located close to an accelerator of cosmic rays and if energetic particles can leave the accelerator site and diffusively reach the cloud. We consider here the situation in which a molecular cloud is located in the proximity of a supernova remnant which is efficiently accelerating cosmic rays and gradually releasing them in the interstellar medium. We calculate the multiwavelength spectrum from radio to gamma rays which is emerging from the cloud as the result of cosmic ray interactions. The total energy output is dominated by the gamma ray emission, which can exceed the emission in other bands by an order of magnitude or more. This suggests that some of the unidentified TeV sources detected so far, with no obvious or very weak counterparts in other wavelengths, might be in fact associated with clouds illuminated by cosmic rays coming from a nearby source. Moreover, under certain conditions, the gamma ray spectrum exhibit a concave shape, being steep at low energies and hard at high energies. This fact might have important implications for the studies of the spectral compatibility of GeV and TeV gamma ray sources.

Key words:
is not observed. However, this argument is not robust given the uncertainties related to the heating of electrons at shocks, and it has been strongly questioned (Tanaka et al. 2008; Morlino et al. 2008; Völk et al. 2008; Gabici 2004; Drury et al. 2008). Moreover, it has been shown that the downstream proton temperature can be effectively reduced if the shock is effectively accelerating cosmic rays. This would also suppress the electron temperature and the thermal X-ray emission (Drury et al. 2008; Helder et al. 2008). A conclusive proof of the hadronic nature of the gamma-ray emission will possibly come from the detection of neutrinos from SNRs, which are expected to be produced during the same hadronic interactions responsible for the production of gamma rays (Kappes et al. 2005; Costantini and Vissani 2005; Gabici and Aharonian 2007).

However, since the detection of neutrinos appears challenging even for km$^{-2}$-scale neutrino telescopes, the search for evidence of CR proton acceleration coming from gamma ray or multi wavelength observations is mandatory.

The presence of a massive molecular cloud close to a SNR can provide a dense target for CR hadronic interactions and thus enhance the expected gamma-ray emission. A correlation between SNRs and molecular clouds is expected, especially in star forming regions (Montmerle 1974). In general, a spatial correlation between TeV gamma rays and dense gas, though not conclusive, would favor an hadronic scenario, where gamma rays are the result of the interactions of CR protons in the dense gas. Such correlation has been observed from a number of SNR/molecular clouds associations (Aharonian et al. 2008b; Albert et al. 2007; Aharonian et al. 2008d). If the molecular cloud is overtaken by the SNR shock, the enhanced gamma-ray emission is expected to be co-spatial with the SNR shell, or with a portion of it (Aharonian et al. 1994). If the cloud is located at some distance from the SNR, it can still be illuminated by CRs that escape from the SNR and produce gamma rays there (Aharonian and Attevian 1996; Gabici and Aharonian 2007). For this scenario, it has been shown that, for typical SNR parameters and for a distance $D = 1$ kpc, a molecular cloud of mass $10^4 M_\odot$ can emit TeV gamma rays at a detectable level if it is located within few hundred parsecs from the SNR (Gabici and Aharonian 2007). This implies that the angular displacement between the SNR shell and the gamma ray emission is of the order of $\delta \approx 6'(D/1 $Kpc$)^{-1} (d_{cl}/100 $pc$)$, where $d_{cl}$ is the distance between the SNR and the cloud. This translates in the fact that sometimes the association between SNRs and molecular clouds can be not so obvious, given that the separation between the two objects can be even larger than the detector’s field of view. Following this rationale, Gabici and Aharonian (2007) proposed that some of the unidentified TeV sources detected by HEGRA (Aharonian et al. 2002), H.E.S.S. (Aharonian et al. 2006a) and MILAGRO (Abdo et al. 2007) might in fact be such clouds illuminated by a nearby SNR.

In this paper, we calculate the expected non-thermal emission, from radio to multi-TeV photons, from a molecular cloud illuminated by CRs coming from a nearby SNR. We generalize the model presented by Gabici and Aharonian (2007), which was limited to the hadronic TeV photons only, to include the generation of secondary electrons in the cloud and the related synchrotron and Bremsstrahlung emission. We found that the total radiation energy output from a cloud is dominated by the gamma ray emission, which can exceed the emission in other bands by an order of magnitude or more. This suggests that some of the unidentified TeV sources detected so far, with no obvious or very weak counterparts in other wavelengths (the so called ”dark sources”), might be in fact associated with massive molecular clouds illuminated by CRs. Moreover, under certain conditions, the gamma-ray spectrum from the cloud exhibit a concave shape, being steep at low ($\sim$ GeV) energies and hard at high ($\sim$ TeV) energies. This fact might have important implications for the studies of the spectral compatibility of GeV and TeV gamma ray sources.

## 2 THE MODEL

Consider a supernova of total energy $10^{51} E_{51} \text{erg}$ exploding in a medium of density $n$. The initial shock velocity is $10^3 u_0 \text{ cm/s}$ and remains roughly constant until the mass of the swept up material equals the mass of the ejecta. This happens at a time $t_{sed} \approx 200 [E_{51}/(n u_0^2)]^{1/3} \text{yr}$, when the shock radius is $R_{sh} \approx 8.5 [E_{51}/(n u_0^2)]^{1/5} \text{pc}$. Then the SNR enters the Sedov phase and the shock radius and velocity scales with time as $R_{sh} \propto t^{2/5}$ and $u_{sh} \propto t^{-3/5}$.

The spectrum of particles accelerated at the SNR shock is determined by the transport equation (e.g., Drury 1983):

$$\frac{\partial f}{\partial t} - \nabla D \nabla f + u \nabla f - \frac{\nabla u}{3} \frac{\partial f}{\partial p} = 0,$$

where $D = D(p)$ is the momentum dependent diffusion coefficient and $u$ the flow velocity. For a strong shock with compression factor $r_s = 4$, the test particle theory predicts an universal shape for the CR spectrum at the shock $f_0(p) \propto p^{-3}$ (Drury 1983). If the shock is an efficient accelerator (as SNR shocks are believed to be), the CR pressure modifies the flow structure, making the shock more compressible and the spectrum of the accelerated particles harder, $f_0(p) \propto p^{-\alpha}$ with $3.5 \lesssim \alpha \lesssim 4$ (Malkov and Drury 2001).

Detailed calculations compared with multiwavelength observations of SNRs suggest the values $r_s \approx 7$ and $\alpha \approx 3.7$ (Ellison et al. 2007; Berezhko and Völk 2006), which we adopt in the following.

The maximum momentum of the accelerated particles is determined by a confinement condition, namely that the diffusion length $l_d$ of the particles cannot exceed the characteristic size of the system $R_{sh}$:

$$l_d = \frac{D(p_{max})}{n_{sh}} \lesssim R_{sh}. \quad (2)$$

The maximum possible energies are achieved when the acceleration proceeds in the Bohm diffusion limit, $D \propto p/B_{sh}$, with $B_{sh}$ the magnetic field strength at the shock. In this case the maximum momentum decreases with time as $p_{max}(t) \propto B_{sh} t^{-1/5}$. In fact, the drop of $p_{max}$ is even faster, given that the magnetic field is also expected to decrease with time. This implies that at any time, particles with momentum above $p_{max}(t)$ quickly escape the remnant, generating a cutoff in the spectrum. The spectrum of the runaway particles can be approximated as a $\delta$–function (see Ptuskin and Zirakashvili 2003):

$$q_{esc}(p,t) = - \delta(p - p_{max}).$$
where the integration has to be performed where the integrand is negative. Thus, to calculate the flux of the run-away particles one has to know: (i) the CR particle distribution function at $p_{max}$ at any location in the SNR, (ii) the flow velocity both inside the shock and outside it, where the CR precursor forms and (iii) how the maximum momentum varies during the SNR evolution. Ptuskin and Zirakashvili (2005) showed that it is straightforward to derive (i) and (ii) using an approximate (but still reasonably accurate) linear velocity profile inside the SNR:

$$u = \left(1 - \frac{1}{\tau_s}\right) \frac{u_{sh}(t)}{R_{sh}(t)} R$$

and assuming that the CR pressure at the shock $P_{sh}^{CR}$ is a fraction $\xi_{CR}$ of the incoming ram pressure $g \nu_{sh}^2$ and that $f_0(p_{max}) \propto P_{sh}^{CR}$.

The determination of $p_{max}$ and its evolution with time requires the knowledge of the diffusion coefficient (see Eq. (2)), which is in turn determined by the level of magnetic turbulence generated by the accelerated particles themselves. This makes the problem nonlinear and very difficult to be solved. The value of $p_{max}$ depends on a few crucial but poorly known aspects of the problem, including the nature of CR-driven instability operating in the shock precursor and the level of wave damping (Bell and Lucek 2003; Bell 2004; Ptuskin and Zirakashvili 2003; Blasi et al. 2007; Vladimirov et al. 2006). Because of these uncertainties, we adopt here a phenomenological approach, namely we parametrize the maximum momentum as $p_{max}(t) \propto t^{-\delta}$. We further assume $p_{max} \approx 5$ PeV and $\sim 1$ GeV at the early ($t = 200$ yr) and late ($t = 5 \times 10^3$ yr) epochs of the Sedov phase respectively. This requires $\delta \approx 2.48$. Remarkably, if the maximum momentum is a power law function of time, the spectrum of the escaping particles integrated over the whole Sedov phase is also a power law of the form $\propto t^{-\frac{8}{5}}$ (Ptuskin and Zirakashvili 2003), which is close (slightly harder) to what needed to fit the CR data below the knee (Berezinskii et al. 1990).

Following Ptuskin and Zirakashvili (2003), the approximate spectrum of the CRs inside the SNR $f_{out}(R, p, t)$ can be obtained from Eq. (1) by dropping the diffusion term, while the spectrum of the runaway CRs at a given distance $R$ from the SNR and at a given time $t$ can be obtained by solving the diffusion equation:

$$\frac{\partial f_{out}}{\partial t}(R, p, t) = D_{ISM}(p) \nabla^2 f_{out}(R, p, t) + q_{esc}(p, t) \delta(R)$$

The diffusion coefficient $D_{ISM}(p)$ describes the propagation of CRs in the galactic disk. The available CR data require a power-law energy dependence, $D_{ISM}(E) \propto E^{-\alpha}$, with $D_{ISM} \approx 10^{25}$ cm$^2$/s at $E \approx 10$ GeV and $\alpha \approx 0.3 \div 0.7$ (Berezinskii et al. 1990). The constraints on the diffusion coefficient are obtained from the comparison between diffusion models and CR data and have to be considered as average galactic values. However, the conditions might be rather different in regions close to CR sources, in particular due to the presence of strong gradients in the CR distribution, which may enhance the generation of plasma waves and thus suppress the diffusion coefficient (Wentzel 1974; Ptuskin et al. 2008). The change in $s$ within the allowed range or the choice of a different normalization for $D_{ISM}$ does not alter qualitatively the results, the main effect being that the characteristic time scales of the problem change proportional to $1/D_{ISM}$.

Remarkably, if $p_{max}(t)$ scales as a power law of time, Eq. (1) can be solved analytically and the distribution function of escaping cosmic rays at any given distance $R$ from the SNR and at any given time $t$ reads, for energies $E \geq c \cdot p_{max}(t)$:

$$f_{out}(t, R, E) = \frac{nE_{SN}}{\pi^{3/2} \ln(E_{MAX}/E_{MIN})} \frac{E}{R_d} E^{-2}$$

where $E_{SN}$ is the total supernova explosion energy, $n$ is the fraction of such energy converted into CRs and $E_{MAX}$ and $E_{MIN}$ are the maximum and minimum energies of CRs accelerated during the Sedov phase. The diffusion distance for a CR of energy $E$ is:

$$R_d(E) = \sqrt{AD(E)(t - \chi(E))}$$

where $\chi(E) = t_{Sedov} \left( \frac{E}{E_{MAX}} \right)^{-1/\delta}$ represents the time after the supernova explosion at which CRs with energy $E$ are released in the interstellar medium. The solution derived by Ptuskin and Zirakashvili (2005) for the total CR spectrum injected by a SNR in the interstellar medium during the whole Sedov phase can be easily derived by integrating Eq. (1) over space. Finally, it has to be noticed that the total CR spectrum at a given time and at a given distance from the SNR is the sum of two contributions: i) a time dependent contribution from CRs coming from the SNR, whose spectrum is described by Eq. (2) and ii) a steady contribution from the galactic CR background.

Following the procedure described above, it is possible to evaluate, for any given time, the CR spectrum in proximity of a molecular cloud located at a given distance from the SNR. If the diffusion coefficient inside the cloud is not significantly smaller than the Galactic one, CR freely penetrate the cloud and the CR spectrum inside the cloud is not affected by propagation effects. Conversely, if the diffusion coefficient is significantly (more than one order of magnitude) reduced, low energy CRs are excluded from the cloud and a low energy cutoff appears in the CR spectrum, at an energy that depends on the value of the diffusion coefficient (see Gabici et al. 2007, for details). Here, we assume free penetration of CRs and we refer the reader to Gabici et al. (2007) (and references therein) for a detailed discussion on CR exclusions from molecular clouds. We do not consider here any contribution from CR electrons coming from the SNR, since they do not escape the remnant due to diffusive confinement (for low energy electrons) and severe synchrotron losses in the strong magnetic field (for high energy electrons).

CR protons propagating inside a molecular cloud produce secondary electron-positron pairs during inelastic interactions in the dense intercloud medium. We calculate the spectrum of the injected secondary electrons $Q_e(t, E)$ by using the parameterization given by Keher et al. (2006) and we follow the time evolution of the electron distribution function $f_e(t, E)$ by solving the equation:

$$\frac{\partial f_e(t, E)}{\partial t} = \frac{\partial}{\partial E} \left( \left( \frac{dE}{dt} \right)_e f_e(t, E) \right) + Q_e(t, E) - \frac{f_e(t, E)}{\tau_{esc}}$$

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where \((dE/dt)_e = E/\tau_{\text{loss}}\) is the energy loss rate for electrons, \(\tau_{\text{loss}}\) the energy loss time, and \(\tau_{\text{esc}}\) the diffusive escape time from the cloud. All these time scales will be discussed and estimated in section 4. Once the proton and electron CR spectra have been derived, the non-thermal radiation from the molecular cloud can be calculated.

3 COSMIC RAY SPECTRUM AT THE CLOUD LOCATION

We consider here a molecular cloud located at a given distance \(d_c\) from a SNR and we calculate the CR spectrum at the cloud location. As mentioned above, the spectrum is the sum of two distinct components: i) the CRs coming from the nearby SNR, described by Eq. [4] and ii) the galactic CR background, which results from the superposition of all the CR sources in the Galaxy. While the latter contribution is constant in time, the first one changes, since the flux of CRs escaping from the SNR evolves in time as described in Sec. 2.

Fig. 1 shows the spectrum of CRs at the location of the molecular cloud. The Galactic CR background is plotted as a thin dot-dashed line labeled as CR sea, while the spectrum of the CRs coming from the SNR is plotted as a thin line for different times after the supernova explosion: 500 yr (solid), 2000 yr (dotted), 8000 yr (short – dashed) and 32000 yr (long-dashed). Thick lines represent the sum of the two contributions. The distance between the SNR and the molecular cloud is 50 pc (left panel) and 100 pc (right panel). We assume a total supernova explosion energy of \(10^{51}\) ergs and a high CR acceleration efficiency at the SNR shock equal to \(\eta = 30\%\). The normalization of the CR spectrum at the cloud location is identical to the one observed near the Sun (see e.g. Dermer 1984):

\[ J_{CR}(E) = 2.2 \left( \frac{E}{\text{GeV}} \right)^{-2.75} \text{cm}^{-2} \text{s}^{-1} \text{GeV}^{-1} \text{sr}^{-1} \]

while the diffusion coefficient, needed to evaluate Eq. [2] is taken equal to:

\[ D(E) = 10^{28} \left( \frac{E}{10 \text{ GeV}} \right)^{0.5} \text{cm}^2/\text{s} \]

compatible with CR propagation models (e.g. Berezinskii et al. 1999).

The evolution with time of the CR spectrum at the position of the molecular cloud can be understood as follows. According to the model described in Sec. 2 CRs with different energies leave the SNR at different times. The highest energy \((\sim \text{PeV})\) CRs leave the SNR first, while CRs with lower and lower energy are released at later times. Moreover, higher energy CRs diffuse faster, thus the spectrum of CRs at the cloud exhibit a sharp low energy cutoff at an energy \(E_{\text{low}}\), which moves to lower and lower energies as time passes. The position of the cutoff represents the energy of the least energetic particles that had enough time to reach the cloud.

\[ \tau_{\text{diff}} \sim \frac{R_{cl}^2}{6D(E, B)} \]

where \(R_{cl}\) is the cloud radius and \(D\) is the diffusion coefficient which we assume here to depend on energy and on magnetic field as:

From Fig. 1 it is clear that the influence of the presence of a nearby SNR close to the cloud is reflected in the CR spectrum at the cloud position, but this influence depends on many parameters, such as the distance between the SNR and the cloud, the time since the supernova explosion, and the CR energy. The CRs coming from the SNR dominate the total CR spectrum at high energy, while at lower \((\sim \text{GeV})\) energies the galactic CR background is always the dominant component, unless the molecular cloud is located at distances significantly smaller than \(\approx 50\) pc from the SNR. However, such small distances are comparable to the size of the SNR itself and thus in this case an interaction between the SNR shock and the molecular cloud is expected (see e.g. Aharonian et al. 1994). The investigation of this scenario goes beyond the scope of this paper and thus we limit ourselves to the case in which the distance between the SNR and the cloud is significantly bigger than the size of both objects.

Aharonian and Atoyan (1996) also evaluated the CR spectrum in the vicinity of a CR accelerator by using an approach similar to the one developed here. They made no specific assumption about the nature of the accelerators and solved the CR transport equation by assuming that a power law spectrum of CRs is injected in the interstellar medium. They considered both the case of a continuous injection of particles during the whole lifetime of the accelerator and the case of an impulsive source that releases all the CRs at the same time. The approach we adopt here is different, because it is specific for a given class of sources, namely SNRs. In this specific case, particles having different energies are released at different times in the interstellar medium.

4 RELEVANT TIME SCALES FOR COSMIC RAY PROPAGATION INSIDE A MOLECULAR CLOUD

Molecular clouds are characterized by a wide range of masses, going from \(\approx 10 M_\odot\) to \(10^4 M_\odot\) or even more and have typical sizes ranging from few to few tens of parsecs. The typical density of a cloud is of about few hundred atoms per cubic centimeter, but much higher densities can be found in less massive and smaller (sub-parsec scale) molecular cloud cores, dark clouds or Bok globules (see Stahler and Palla 2005, for a review). The typical magnetic field of the intercloud medium is \(\approx 10 \mu G\) (Shu et al. 1987), and it scales roughly as the square root of the gas density, thus reaching the mG level in the densest regions with density \(10^4 \div 10^6 \text{ cm}^{-3}\) (Crutcher 1999).

The propagation of high energy CRs inside molecular clouds has been studied in Gabici et al (2007) (see also Dogel’ and Sharov, 1990), where an extensive discussion can be found. Here we summarize the most relevant aspects. Once the CRs from the SNR reach the molecular cloud, they diffusively penetrate with typical time scale:

\[ \tau_{\text{diff}} \sim \frac{R_{cl}^2}{6D(E, B)} \]
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Figure 1. Spectrum of CRs at the location of the molecular cloud. The cloud is located at 50 pc (left) and 100 pc (right panel) from a SNR. The thin dot-dashed line shows the Galactic CR spectrum, while the thin solid (curve 1), dotted (2), short-dashed (3) and long-dashed (4) lines represent the spectrum of CRs coming from the SNR for 500, 2000, 8000 and 32000 years after the supernova explosion, respectively. The thick lines show the total CR spectrum at the cloud location.

\[
D(E) = \chi \times 10^{28} \left( \frac{E}{10 \, \text{GeV}} \right)^{0.5} \left( \frac{B}{3 \, \mu \text{G}} \right)^{-0.5} \text{cm}^2/\text{s}.
\]  
(13)

Here \( \chi \) is a factor that takes into account deviations from the average Galactic diffusion coefficient described by Eq. 11 (see Gabici et al. 2007) and \( 3 \, \mu \text{G} \) is the average magnetic field in the Galactic disk. At very high energies, when the Larmor radius of the particle becomes comparable with or even larger than the size of the cloud, particles propagate almost rectilinearly, and the propagation time reduces to the crossing time

\[
\tau_{\text{cross}} = \frac{R_{\text{cl}}}{c}.
\]

In the following we assume the characteristic propagation time for a CR in a molecular cloud to be:

\[
\tau_{\text{prop}} \approx \tau_{\text{diff}} + \tau_{\text{cross}},
\]  
(14)

which is a rough approximation which still describes with sufficient accuracy the two different regimes of propagation.

CRs can freely penetrate the molecular cloud if the diffusion time is shorter than the energy loss time which, for CR protons with energy above \( \sim 1 \text{GeV} \), is dominated by inelastic proton-proton interactions in the dense gas and reads (see e.g. Berezinskii et al. 1990):

\[
\tau_{\text{pp}} = \frac{1}{n_{\text{gas}} \sigma_{\text{pp}}} = 6 \times 10^5 \left( \frac{n_{\text{gas}}}{100 \, \text{cm}^{-3}} \right)^{-1} \text{yr},
\]  
(15)

where \( n_{\text{gas}} \) is the gas density, \( c \) is the speed of light and \( \sigma_{\text{pp}} \) and \( \kappa \) are the cross section and inelasticity of the process, respectively. For nonrelativistic protons (energies below \( 1 \text{ GeV} \)) ionization losses become relevant, with time scale (e.g. Berezinskii et al. 1990):

\[
\tau_{\text{ion}}^p \sim 2.8 \times 10^7 \left( \frac{n_{\text{gas}}}{100 \, \text{cm}^{-3}} \right)^{-1} \times \left( \frac{E_k}{m_p c^2} \right)^{\frac{3}{2}} \left[ 11.8 + \ln \left( \frac{E_k}{m_p c^2} \right) \right]^{-1} \text{yr}.
\]  
(16)

Here \( E_k \) is the proton kinetic energy and \( m_p \) is the proton mass. The total energy loss time for CR protons due to both processes is given by:

\[
\tau_{\text{p}}^\text{loss} = \frac{1}{\tau_{\text{pp}}} + \frac{1}{\tau_{\text{ion}}^p}.
\]  
(17)

Secondary electron-positron pairs are produced inside the cloud during inelastic collisions between CR protons in the dense gas. The typical diffusion time for such electrons is given by Eq. 12 while the relevant channels for electron energy losses are ionization losses, Bremsstrahlung emission and synchrotron emission with characteristic times (e.g. Ginzburg and Syrovatskii 1964):

\[
\tau_{\text{e}}^\text{ion} = 1.9 \times 10^4 \left( \frac{n_{\text{gas}}}{100 \, \text{cm}^{-3}} \right)^{-1} \frac{\gamma}{3 \ln(\gamma) + 18.8} \text{yr},
\]  
(18)

\[
\tau_{\text{Brems}} = 3.3 \times 10^5 \left( \frac{n_{\text{gas}}}{100 \, \text{cm}^{-3}} \right)^{-1} \left( \frac{E}{10 \, \text{TeV}} \right) \left( \frac{B}{10 \, \mu \text{G}} \right)^2 \text{yr},
\]  
(19)

\[
\tau_{\text{syn}} = 1.3 \times 10^5 \left( \frac{E}{\text{TeV}} \right)^{-1} \left( \frac{B}{10 \, \mu \text{G}} \right)^{-2} \text{yr},
\]  
(20)

respectively. Here, \( \gamma \) is the electron Lorenz factor and \( E \) the total electron energy. The ionization losses are computed for ultra-relativistic electrons. The total energy loss time for CR electrons due to the three processes listed above is given by:

\[
\tau_{\text{e}}^\text{loss} = \left( \frac{1}{\tau_{\text{ion}}} + \frac{1}{\tau_{\text{Brems}}} + \frac{1}{\tau_{\text{syn}}} \right)^{-1}.
\]  
(21)

In writing the equation above, we neglected the possible role...
of inverse Compton losses off soft background photons. Such losses are expected to be relevant when the energy density in the radiation field $\omega_{\text{rad}}$ is greater than the magnetic field energy density. In the following we will consider a cloud with radius $R_{\text{cl}} = 20$ pc and magnetic field $B = 20 \mu G$, and in this case the condition reads: $\omega_{\text{rad}} > 10 \left( B/20 \mu G \right)^2 \text{eV}/\text{cm}^3$. Such condition can be realized inside molecular clouds only close to star forming regions. In particular, if a star forming region or a stellar OB association with total photon output equal to $4 \times 10^{38} L/L_\odot \text{erg/s}$ is located within a molecular cloud, inverse Compton losses will dominate over synchrotron losses around the star forming region up to a distance of $R \approx 8 \times 10^{-3} \left( L/L_\odot \right)^{1/2} \left( B/20 \mu G \right)^{-1} \text{pc}$, which becomes comparable with or larger than the molecular cloud radius $R_{\text{cl}}$ when $L \geq 6 \times 10^6 \left( B/20 \mu G \right)^2 \left( R_{\text{cl}}/20 \text{ pc} \right)^2 L_\odot$. Since this is a quite high luminosity, only a small fraction of molecular clouds are expected to host such luminous OB associations (Williams and McKee 1997). We can thus safely neglect the role of inverse Compton losses in most of the situations. Inverse Compton losses can certainly play a role if one considers small regions within the cloud which surrounds star forming regions. Such regions constitute a small fraction of the cloud volume and thus are not expected to affect significantly the non thermal emission from the whole cloud.

In Fig. 2 (left panel) the characteristic time scales listed above have been plotted as a function of particle energy for a giant molecular cloud with total mass $M_{\text{cl}} = 10^5 M_\odot$ and radius $R_{\text{cl}} = 20$ pc. Assuming a flat density profile the density is $n_{\text{gas}} \sim 120 \text{ cm}^{-3}$. The magnetic field is assumed to be $B_{\text{cl}} = 20 \mu G$. The dotted line refers to proton energy losses, which are dominated by ionization losses at energies below $\sim 1 \text{ GeV}$ and by inelastic proton–proton interactions at higher energies. The solid line represents the electron energy loss time. The three different power law behaviors reflect the dominance of ionization, Bremsstrahlung and synchrotron losses at low, intermediate and high energies, respectively. Finally, the dashed line represents the propagation time for particle energies above a few hundreds $\text{TeV}$. The propagation time has been evaluated by using the diffusion coefficient from Eq. (13) with $\chi = 1$ (no suppression with respect to the average Galactic value).

For proton energies above the threshold for pion production ($E_{\pi h} \sim 280 \text{ MeV}$), the propagation time is always shorter than the energy loss time. This means that CR protons which produce gamma rays and secondary electrons can freely penetrate the cloud and their flux is not attenuated due to energy losses. The propagation time for CR electrons is also shorter than the energy loss time for particle energies between $E \sim 100 \text{ MeV}$ and a few hundreds of $\text{TeV}$. This implies that, within this energy range, the secondary electrons produced inside the cloud quickly escape, and have little effect on the non-thermal emission from the cloud. On the other hand, extremely energetic electrons with energies above a few hundreds $\text{TeV}$ radiate all their energy in form of synchrotron photons before leaving the cloud. In a typical magnetic field of a few tens of microGauss, these electrons emit synchrotron photons with energy:

$$E_{\text{syn}} \approx 1 \left( \frac{B_{\text{cl}}}{10 \mu G} \right) \left( \frac{E}{100 \text{ TeV}} \right)^2 \text{keV}. \quad (22)$$

Thus, the most relevant contribution from secondary electrons to the cloud non thermal emission falls in the hard X-ray band.

The middle panel of Fig. 2 shows the time scales for a compact cloud with radius $R_{\text{cl}} = 0.5$ pc and mass $M_{\text{cl}} = 10^3 M_\odot$, which implies, in case of a flat density profile, a density of $\sim 1.6 \times 10^5 \text{ cm}^{-3}$. A strong magnetic field of $300 \mu G$ is assumed, as suggested by observations of very dense clouds (Crutcher 1999). These parameters are typical for molecular...
cloud cores or for dark clouds (Stahler and Palla 2003). The left and middle panels in Fig. 2 look very similar, except for a scaling factor. This implies that the same conclusions can be drawn as for the case of a giant molecular cloud, and thus a similar behavior is expected from giant molecular clouds and compact clouds, the only difference being that all the time scales are much shorter in the latter case, due to the high gas density and to the reduced size of the system.

The properties of giant molecular clouds located in the galactic centre region can differ significantly from the average figures reported above. As an example, we plot in the right panel of Fig. 2 the typical time scales for the SgrB2 cloud. This is a very massive cloud located at 100 pc (projected distance) from the galactic centre. The cloud virial mass is \( M_{ \text{SgrB2}} = 1.9 \times 10^6 M_{\odot} \) (Protheroe et al. 2008) and a magnetic field at the milliGauss level has been measured in the outer envelope of the cloud complex (Crutcher 1999). The mass distribution can be fitted with a radial gaussian density profile with \( \sigma = 2.75 \) pc (Protheroe et al. 2008, and references therein). To compute the curves plotted in Fig. 2 (right panel), we assumed a cloud radius of \( R_{ \text{SgrB2}} = 2\sigma = 5.5 \) pc, which encloses \( \approx 95\% \) of the total cloud mass. This gives an average density of \( n_{\text{gas}} = 1.1 \times 10^3 \text{ cm}^{-3} \) (roughly a factor of 2 below the central density). It is evident from the right panel of Fig. 2 that the SgrB2 cloud is remarkably different from a typical giant molecular cloud. In particular, the very high values of the magnetic field and of the gas density make the energy loss time of CR protons significantly shorter than the propagation time for energies below a few hundred GeVs. Moreover, for CR electrons the energy loss time is always shorter than the propagation time. This means that CR protons with energies up to few hundred GeVs cannot penetrate the molecular cloud, as they do in the cases considered in the left and middle panel of Fig. 2. Primary CR electrons cannot penetrate the cloud, while secondary CR electrons produced inside the cloud in hadronic interactions cannot leave the cloud and radiate all their energy close to their production site. These characteristics make SgrB2 a very peculiar objects whose modelling needs a specific treatment. A detailed study of the CR penetration into the SgrB2 cloud has been performed by Protheroe et al. (2008), who also computed the synchrotron radio emission from secondary electrons. The effects of CRs exclusion from giant molecular clouds on their gamma ray emission have been discussed in detail by Gabici et al. (2007). In the following we will not focus onto any specific object but rather investigate the case of the typical molecular clouds as the ones considered in the left and middle panels of Fig. 2.

To conclude the discussion on characteristic time scales, it is interesting to note that under certain conditions all the energy loss times, for both protons and electrons, scales in the same way with gas density, namely as \( n_{\text{gas}}^{-1} \). This is evident from Eqs. 10 and 13 that describe inelastic proton-proton scattering and ionization losses for protons respectively, and from Eqs. 15 and 18 that describe ionization and Bremsstrahlung losses for electrons respectively. Moreover, also for synchrotron losses (Eq. 20), it is possible to derive the same scaling with gas density by recalling that observations suggest that the magnetic field in molecular clouds scales as the square root of gas density (Crutcher 1999). This has the important consequence that, in typical molecular clouds, particles with a given energy (protons or electrons) lose their energy always through the same channel, independently on the gas density. As said above, this conclusion may not hold for peculiar objects such as SgrB2.

5 NON-THERMAL RADIATION FROM A MOLECULAR CLOUD

Molecular clouds are now established gamma ray sources (Aharonian et al. 2006c, 2006d). Their gamma ray emission is believed to be the result of the decay of neutral pions produced during the inelastic collisions of CRs with the dense gas which constitutes the cloud (Issa and Wolfendale 1981, Aharonian 1991, Gabici et al. 2007). During the same interactions, also electrons and positrons are produced via the decay of charged pions. These electrons and positrons produce a broad spectrum of radiation from radio waves to gamma rays due to synchrotron emission and non thermal Bremsstrahlung.

In this section we compute the expected non-thermal emission from a molecular cloud located in the proximity of a SNR. The emission is the result of CR interactions with the dense gas and magnetic field in the cloud and is made up of two contributions: a steady state contribution from the interactions of background CRs that penetrate the cloud and a time dependent contribution from the interactions of CRs coming from the nearby SNR.

We consider a giant molecular cloud of mass \( M_{\text{cl}} = 10^5 M_{\odot} \), radius \( R_{\text{cl}} = 20 \) pc and we assume an uniform density of \( n_{\text{gas}} \sim 120 \) cm\(^{-3} \). The magnetic field is \( B_{\text{cl}} = 20 \) \( \mu \)G. The relevant time scales for CR propagation and energy losses in such an environment have been plotted in the left panel of Fig. 2. In order to show all the different contributions to the total non-thermal emission, in Fig. 3 we plot the broad band spectrum from the cloud at a time \( t = 2000 \) years after the supernova explosion. The SNR is located 100 pc away from the molecular cloud and the distance to the observer is 1 kpc. The dotted line (curve 3) represents the emission from neutral pion decay (from both background CRs and CRs from the SNR), the dot–dashed lines represent the synchrotron (curve 2) and Bremsstrahlung (curve 4) emission from background CR electrons that penetrate the molecular cloud and the dashed lines represent the synchrotron (curve 1) and Bremsstrahlung (curve 5) emission from secondary electrons produced during inelastic CR interactions in the dense gas. For the spectrum of background CR electrons we use a fit to the measured spectrum at Earth (see Kobayashi et al. 2004 for a recent compilation of data).

Electrons can freely penetrate the cloud except for the highest (\( \gtrsim 300 \) TeV) and lowest (\( \lesssim 100 \) MeV) part of the energy spectrum, where the energy loss time scale is significantly shorter than the propagation time (see Fig. 2). For these energies the CR electron flux inside the cloud is suppressed and we estimated the suppression by assuming that CR electrons can penetrate undisturbed the cloud only up to a given depth, which is estimated as \( c t_{\text{loss}} \) and \( \sqrt{D_{\text{loss}}} \) for the high and low energy end of the spectrum respectively. This approximation is satisfactory for the purposes of this paper, given that the suppression becomes crucial only for particles which emit negligible non-thermal emission.

The decay of neutral pions dominates the total emission for energies above \( \approx 100 \) MeV. The two peaks in the
emission reflects the shape of the underlying CR spectrum, which, as illustrated in Fig. 1, is the sum of the steep background CR spectrum, which produces the $\pi^0$-bump at a photon energy of $m_{\pi^0}/2 \sim 70$ MeV (in the photon flux $F$), and an hard CR component coming from the SNR that produces the bump at higher energies. The flux level at 1 TeV is approximately $5 \times 10^{-12} \text{erg/cm}^2/\text{s}$, detectable by currently operating Imaging Atmospheric Cherenkov Telescopes, even taking into account the quite extended ($\approx 2\degree$) nature of the source. It is remarkable that such a cloud would be detectable even if it were located at the distance of the Galactic centre, as can be easily estimated by taking into account that the sensitivity of a Cherenkov telescope like H.E.S.S. after 50 hours of exposure, is $\approx 10^{-13}(\theta_s/0.1\degree)\text{TeV/cm}^2/\text{s}$, where $\theta_s$ is the source extension. This means that very massive clouds can be used to reveal the presence of enhancements of the CR density in different locations throughout the whole Galaxy. Similar conclusions can be drawn for the expected emission in the GeV range, which is currently probed by the AGILE and FERMI satellites. In particular, FERMI, with a point source sensitivity of $\lesssim 10^{-9}\text{GeV/cm}^2/\text{s}$ at energies above 1 GeV (www-glast.slac.stanford.edu), will be able to detect such giant molecular clouds as extended sources if they are located within $1\pm 2$ kpc from the Earth, or as point sources if they are at larger distances. Such a use of molecular cloud as CR barometers has been discussed in several papers for both GeV [Issa and Wolfendale 1981] and TeV gamma rays [Aharonian 1991]. Here we demonstrated that SNRs can provide enhancements in the CR density that can generate gamma ray fluxes well within the capabilities of currently operating instruments.

Figure 3. Broad band spectrum for a molecular cloud of mass $10^{5}M_{\odot}$, radius 20 pc, density $\sim 120\text{ cm}^{-3}$, magnetic field $20\mu\text{G}$. The molecular cloud is at 100 pc from a SNR that exploded 2000 yr ago. The distance of the cloud is 1 kpc. The dotted line shows the emission from $\pi^0$-decay (curve 3), the dot-dashed lines represent the synchrotron (curve 2) and Bremsstrahlung (curve 4) emission from background CR electrons that penetrate the molecular cloud and the dashed lines the synchrotron (curve 1) and Bremsstrahlung (curve 5) emission from secondary electrons.

The possibility of detecting sources with such a distinct spectrum is also relevant for the issue of identifying GeV and TeV unidentified sources. One of the criteria suggested to support an association between a GeV and TeV source is, beside the positional coincidence, the spectral compatibility. In a recent paper, Funk et al. (2008), investigated the spectral compatibility of EGRET and H.E.S.S. unidentified sources located in the inner Galactic region. For sources showing positional coincidence, they found generally a good spectral compatibility. Thus, a loose association between a SNR and a massive molecular clouds as the one studied here, is expected to be characterized, at least at some stage of the SNR evolution, by a very peculiar spectrum which is steep at low (GeV) energies and hard at high (TeV) energies.

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Non-thermal emission from molecular clouds

Figure 4. Time dependence of the broad band spectrum for the same giant molecular cloud considered in Fig. 3. The solid, dotted, short-dashed and long-dashed lines refer to the emission at a time 500, 2000, 8000 and 32000 years after the explosion. The dot-dashed line represents the spectrum of a molecular cloud with no SNR in its proximity.

(GeV–TeV) energy range and discussed the implications of adding a high or low energy cutoff. The scenario presented here adds the new interesting possibility of a single source showing a dramatically different behavior at GeV and TeV energies, namely a spectrum which shows a significant hardening at higher energies.

The evolution with time of the emission from the cloud is shown in Fig. 4 where the solid, dotted, short-dashed and long-dashed lines show the spectrum at a time equal to 500, 2000, 8000 and 32000 years after the supernova explosion respectively. For comparison, the emission from a molecular cloud, with no SNR located in its proximity, is plotted as a dot-dashed line. In this case, only background CRs that penetrate the molecular cloud contribute to the emission.

It is evident from Fig. 4 that the radio (λ ≥ 0.1mm) and the soft gamma ray (≈ 1 MeV ÷ 1 GeV) emission from the cloud is constant in time. This reflects the fact that such emission is produced by background CRs that enter the cloud. The emission in the other energy bands is variable in time, being produced by the CRs coming from the SNR. The flux of this latter component changes with time as indicated in Fig. 4. The two most prominent features in the variable emission are two peaks, in X- and gamma-rays respectively.

The peak observable at gamma ray energies is the result of the decay of neutral pions produced when CRs of different energies coming from the SNR reach the cloud at different times. The peak moves at lower and lower energies with time, reflecting the fact that CRs with lower and lower energies progressively reach the cloud as time flows. At early times, the emission can extend up to ~ 100 TeV (solid line), revealing the presence of PeV CRs and thus indirectly the fact that the nearby SNR is acting as a CR pevatron (see Gabici and Aharonian 2007, for a discussion of this issue). Moreover, the gamma ray emission in the TeV range is enhanced with respect to the one expected from an isolated molecular cloud (dashed-dotted line in Fig. 4) for a period of several 10^9 yr. This is much longer than the period during which SNRs are effectively accelerating the multi-TeV CRs responsible for the TeV emission, which lasts few thousands years. This is because the duration of the gamma ray emission from the cloud is determined by the time of propagation of CRs from the SNR to the cloud and not by the much shorter CR confinement time in the SNR. Therefore, the gamma ray emission from the cloud lasts much longer than the emission from the SNR, making the detection of clouds more probable (Gabici and Aharonian 2007).

The peak in the X-ray spectrum is due to synchrotron emission from secondary electrons produced in CR interactions in the cloud. The peak is moving to lower energies with time but, unlike the gamma ray peak, it is also becoming less and less pronounced. This fact can be understood with the help of Fig. 2 (left panel). After 500 yr from the supernova explosion (solid line in Fig. 4), PeV CRs from the SNR reach the cloud and produce there secondary electrons with energy in the ≈ 100 TeV range. For these electrons, the synchrotron cooling time is comparable with the escaping time from the cloud. Thus, they release a considerable fraction of their energy in form of X-ray synchrotron photons before leaving the cloud. As time passes, lower energies CRs reach the cloud and secondary electrons with lower energies are produced. For these electrons the cooling time becomes progressively longer than the escape time and this explain the suppression of the synchrotron emission. The X-ray synchrotron emission is weaker than the TeV emission for any time and for times > 2000 yr the ratio between TeV and keV emission can reach extreme values of a few tens or more. These values are observed from some of the unidentified TeV sources such as HESS J1616-508 (Matsumoto et al. 2007; Bamba et al. 2007) and more in general unidentified TeV sources are characterized by the absence of any clear counterpart at other wavelengths. Due to this peculiar spectral properties, such sources have been labeled as dark, since they seemed to emit gamma rays only. However, in the scenario presented in this paper, spectra showing a high TeV/keV flux ratio can be produced very naturally if a cloud is illuminated by CRs coming from a nearby SNR. This suggestion is also supported by the fact that most of the unidentified TeV sources are spatially extended, as molecular clouds are expected to be.

In the hard X-ray/soft gamma ray region of the spec-
trum (from tens of keVs to hundreds of MeVs), partially covered by the INTEGRAL satellite, extremely hard spectra \(dN/dE \propto E^{-1}\) may result due to the Bremsstrahlung emission from primary and secondary CR electrons.

Finally, the radio emission from the cloud is the result of the synchrotron emission of background CR electrons that penetrate the cloud. The contribution from secondary electrons is subdominant, due to the fact that the ∼ GeV secondary electrons that might emit synchrotron radio waves escape from the cloud before losing energy (see Fig. 4). Moreover, in the GeV energy range, ionization and Bremsstrahlung losses dominate, and this would further reduce the expected synchrotron emission. Recently, Protheroe et al. (2008) estimated the expected synchrotron radio emission from secondary electrons produced by CR interactions in the Sgr B2 giant molecular cloud. They did not consider the contribution from background CR electrons and neglected the effects of diffusive transport of secondary electrons (namely, they assumed no penetration of electrons from outside the cloud and instantaneous cooling of secondary electrons produced inside the cloud). These assumptions are valid for the very strong magnetic field of the order of one milliGauss measured for SgrB2. Such field is much stronger than the one assumed here. Thus, due to these somewhat extreme assumptions, possibly justified in the particular case of Sgr B2 cloud, a direct comparison between their findings and the results presented in this paper is not straightforward. Protheroe et al. (2008) also noticed that the radio emission from a cloud at frequencies above ∼ 1 GHz can be dominated by free–free thermal emission. Being focused on the non-thermal emission from clouds, we did not attempt here to model their thermal emission. However, our findings can still be tested and constrained by observations in the GHz range. This can be done by requiring the predicted synchrotron emission not to overproduce the observed free–free thermal emission. A similar approach has been adopted by Jones et al. (2008).

5.1 The spectral shape at GeV-TeV energies

As noticed in the previous section, concave gamma ray spectra may be produced in a molecular cloud located in proximity of a SNR, as the result of the decay of neutral pions produced in CR interactions. Such concavity reflects the shape of the underlying CR spectrum, which consist of the superposition of two components: the galactic CR background, characterized by a steep spectrum, and the CRs coming from the nearby SNR, which exhibit a hard spectrum. With this respect, the distance between the SNR and the molecular cloud plays a crucial role. This is because, the larger the distance between the SNR and the cloud, the lower the level of the CR flux coming from the SNR. Moreover, also the time evolution of the emission from a cloud changes with since it takes a particle with given energy to cover such a distance scales as \(t \propto d^2/\dot{D}\), where \(D\) is the diffusion coefficient.

In Fig. 5 the total gamma ray spectrum from a molecular cloud is shown as a function of the distance between the SNR and the cloud. The cloud mass is \(10^5 M_\odot\) and the distance from the SNR is 50, 100 and 200 pc for the left, central and right panel, respectively. Similarly to Fig. 4 the solid, dotted, short-dashed and long-dashed lines refer to the emission for 500, 2000, 8000 and 32000 years after the supernova explosion. It is evident from Fig. 5 that a great variety of gamma ray spectra can be produced. In almost the entirety of the cases considered, the gamma ray emission is characterized by the presence of two pronounced peaks. The low energy peak, located in the GeV domain is steady in time and it is the result of the decay of neutral pions produced in hadronic interactions of background CRs in the dense intercloud gas. The high energy peak is the result of hadronic interactions of CRs coming from the nearby SNR, and thus it is moving in time to lower and lower energies (see previous section for a discussion). Both the relative intensity and position of the two peaks depend on the distance between the SNR and the cloud. Interestingly, the GeV emission from the cloud is affected by the presence of the nearby SNR only at late times after the explosion and only if the distance from the SNR is comparable or smaller than \(\approx 50\) pc (see Fig. left panel). In all the other cases the GeV emission is always the result of the interactions of background CRs and thus, at least in this case, observations of molecular clouds in the GeV gamma ray domain cannot be used to infer the presence of a CR accelerator located at a distance greater that \(\approx 50\) pc from the cloud.

Similar concave or “V–shaped” spectra have been recently obtained by Rodriguez Marrero et al. (2008) in a different context in which two molecular clouds are assumed to be located in the proximity of a CR accelerator. If the two clouds happen to be located at different distances from the CR accelerator but within an angular separation smaller than the FERMI angular resolution, then they would appear as a single GeV source, and the superposition of their emission might result in concave spectra. However, Rodriguez Marrero et al. (2008) did not include in their calculations the contribution to the emission coming from the ubiquitous galactic CR background, which in most cases dominates over the contribution of CRs from the nearby SNR, at least for what concerns the GeV emission from the cloud (see e.g. Fig. 4). Moreover, they also considered very short distances between the cloud and the CR accelerator (down to 5 pc), but in this case an accurate modeling of the CR accelerator itself is needed, especially for what concerns its own gamma ray emission that might add up to the total emission. In addition to that, distances as short as \(\approx 5 \div 10\) pc are, under many circumstances, smaller than both the source size and the radius of the molecular cloud itself, and this changes significantly the problem since the interactions between the accelerator and the MC are likely to play an important role.

The prediction of V-shaped spectra that we make in this paper is more general than the one by Rodriguez Marrero et al. (2008), since it represents an intrinsic feature of a single molecular cloud which is located close to a CR source. The V-shaped gamma ray spectrum reflects the shape of the underlying CR spectrum which is the superposition of the steep spectrum of the background CRs and the hard spectrum of CRs coming from the nearby SNR.

5.2 The role of the magnetic field

The value of the magnetic field in the cloud is an important parameter since it regulates the synchrotron energy losses of high energy electrons, and the diffusive escape time of relativistic particles from the cloud. Observations suggest that
Figure 5. Total gamma ray emission from a molecular cloud of mass $10^5 M_\odot$ located at a distance of 1 kpc. The distance between the molecular cloud and the SNR is 50, 100 and 200 pc for left, centre and right panel, respectively. As in Fig. 4, the solid, dotted, short–dashed and long–dashed lines refers to the emission at a time 500, 2000, 8000 and 32000 years after the explosion.

The value of the magnetic field in a molecular cloud scales with the square root of the gas density, reaching very high values (1 mG or more) in the very dense sub-parsec scale cloud cores (Crutcher 1999). However, dense cores constitute a very small fraction of the total volume of molecular clouds. Since here we are interested in calculating the emission from the whole cloud, the relevant parameter is the volume averaged value of the cloud magnetic field. It seems reasonable to assume that the total magnetic energy in the cloud $W_B = (B^2/8\pi) \times V$, where $V$ is the cloud volume, does not exceed the total gravitational energy of the cloud $W_G = 3GM^2/5R_{cl}$. This leads to a maximum value of the average magnetic field of: $B \leq 30 (M/10^5 M_\odot)(R_{cl}/20\text{pc})^{-2}\mu\text{G}$. This is in general agreement with observations, from which a value of $\approx 10 \mu\text{G}$ can be inferred for typical cloud densities of $\approx 100 \text{ cm}^{-3}$. However, since the dispersion around this mean value is considerable (see e.g. Crutcher 1999), it is worth to investigate how the non thermal emission from a molecular cloud depends on the actual value of the magnetic field.

Fig. 6 shows the broad band spectrum from a molecular cloud of mass $10^5 M_\odot$, radius 20 pc, density $\sim 120 \text{ cm}^{-3}$. The distance between the cloud and the SNR is 50 pc. In the top and bottom panels is plotted the cloud emission after 500 and 2000 years from the supernova explosion, respectively. The solid line refers to a value of the magnetic field of 30 $\mu\text{G}$, while the dashed line represents the emission for a smaller value of the field equal to 10 $\mu\text{G}$. The cloud emission from radio frequencies up to the hard X-ray band strongly depends on the value of the magnetic field, while the gamma ray emission is unaffected, being the result of hadronic interactions of CR protons. The strong dependence of the radio and X-ray emission on the magnetic fields is evident, and this demonstrate that this effect has to be taken into account in multi wavelength studies of molecular clouds.

6 CONCLUSIONS
The non thermal emission from a molecular cloud located in proximity of a SNR is the result of the interactions of CRs that penetrate the cloud. Both CRs in the galactic background and runaway CRs from the SNR contribute to the emission. In this paper, we calculated the expected non thermal emission from the molecular cloud as a function of several parameters, such as the time after the supernova explosion, the distance between SNR and cloud, and the cloud magnetic field. In all the cases, the gamma ray emission from the cloud is by far exceeding the energy output in other energy bands.

The gamma ray emission from the cloud consists of two distinct components. The first one is due to the interactions of CRs from the galactic background, which are characterized by a steep spectrum. This component is steady in time...
and peaks in the GeV energy region. The second component
is the result of the interactions of runaway CRs that escape
the SNR and diffusively reach the cloud. The spectrum of
these runaway CRs is hard and variable in time and both
this characteristics are reflected in the related gamma ray
emission. In particular, this component is producing a sec-
ond peak in the gamma ray spectrum which moves to lower
and lower energies, reflecting the fact that high energy CRs
are released from the SNR earlier and diffuse faster than
low energy ones, and as a consequence they reach the cloud
earlier. The superposition of these two components of the
Gamma radiation might be soon revealed.

It has been suggested that some of the dark TeV
unidentified sources, with no obvious counterparts at
any other wavelength, might be indeed associated with
molecular clouds illuminated by CRs from nearby ac-
celeorators such as SNRs (Aharonian and Atoyan 1996;
Gabici and Aharonian 2007). We showed here that, in this
scenario, the “darkness” of a source, often defined as the
ratio $R_{\gamma/X}$ between the TeV and X-ray observed flux,
depends on several parameters such as the distance between
the SNR and the cloud, the time after the supernova
explosion and the value of the magnetic field in the molec-
ular cloud. However, in most cases it is very natural to obtain
very high values for $R_{\gamma/X}$, compatible with the estimates
on $R_{\gamma/X}$ claimed for some of the unidentified TeV sources
(see e.g. Bamba et al. 2007; Bamba et al. 2008). This further
support an association between unidentified TeV sources
and molecular clouds and suggests that the unknown
nature of these objects might be soon revealed.

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