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Young star clusters as gamma ray emitters and their detection with Cherenkov Telescopes

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Abstract: Young massive star clusters as sites of strong stellar winds and supernova explosions may accelerate charged particles at high energies and produce gamma-rays. These sources may also contribute to the production of cosmic rays in our galaxy. At TeV energies several candidates have already been detected: Cygnus OB2, Westerlund 1 & 2, W43, Pismis 22 and W49A. Our study addresses the issue of very young star clusters where no supernova has occurred yet. During the lifetime of a massive star ($M > 20M_{\odot}$), supersonic stellar winds do indeed release as much energy as a supernova explosion. As supernova remnants are already known as gamma-ray emitters our purpose is to avoid any ambiguity on the origin of a possible gamma ray emission and to fully assume a stellar wind contribution. In this work we present a sample of potential gamma-ray emitting clusters and discuss the criteria used to build the sample. We hence model the expected energetic particle spectrum considering a source term from the star cluster's bubble and the escape time from the HII region around. We deduce gamma-ray luminosities produced by pion decay emission. We finally compare the expected gamma-ray flux with HESS-II and CTA Cherenkov telescopes sensitivities for two selected clusters.

Keywords: gamma-ray astronomy, young star clusters

1 Introduction

Very High Energy gamma-ray astronomy ($E > 30$ GeV) has known a rapid expansion these last ten years thanks to the H.E.S.S., VERITAS and MAGIC experiments. The main galactic sources are SuperNova Remnants (SNR), Pulsar Wind Nebulae (PWN) and stellar binaries (for a review see [1]). These objects are deeply studied and outstandingly well described as sites presenting strong shocks in regard to their high energy released. Given the latter parameter massive stars are interesting through their stellar winds. Integrated on its lifetime (~ 3.45 Myr) the mechanical energy released by a star of about $60 M_{\odot}$ is comparable to the one of a supernova ($\sim 10^{51}$ erg). This phenomenon is further amplified if we consider that the majority of stars forms in clusters [2]. This makes massive star clusters interesting candidates as gamma-ray emitters even if few of them has been detected so far : Cygnus OB2, Westerlund 1 & 2, W43, Pismis 22 and W49A.

Clusters of massive stars form in Giant Molecular Clouds (GMCs) in groups called OB associations. Initially the stars are deeply embedded in their parent molecular cloud [5]. Their powerful stellar winds create a surrounding bubble with a structure comparable to a supernova remnant (shock wave, reverse shock, kinetic energy transferred to the interstellar medium) [6]. Their ionizing radiation creates a HII region surrounding the cluster and its bubble. So the surrounding GMC is disrupted and continuously destroyed. The lifetime of a typical GMC is then about 10^7 yr [7]. The Rosette nebula presents this structure : a cluster surrounded

by an interstellar bubble, a HII Region and a GMC [8].

Here, we propose to model the gamma-ray emission from star clusters with such a structure assuming a hadronic origin. To predict the gamma-ray flux we assume that the acceleration region volume is the interstellar bubble. As the bubble is a rarefied zone ($n < 10^{-2}$ cm⁻³), we assume that most of the radiation is produced by the HII region which has the highest densities directly around the cluster ($n \sim 10^2$ cm⁻³). We build a sample of promising star clusters from parameters derived in the model. Finally, we discuss and constrain two parameters of our model in the case of two star clusters.

2 Modeling the gamma-ray emission from star clusters

Our model assume a point-like object with a given stellar wind luminosity. The structures around the cluster are assumed to have a spherical geometry. First, the interstellar bubble is considered as the region of acceleration : a shock wave is expected at the border of the freely flowing stellar winds. Then the HII region (ionized part of the surrounding molecular cloud) is considered as the region of gamma-ray emission.

We adopt a one-zone hadronic model where the proton spectrum is given by a diffuse equation :

$$\partial_t N(E, t) = \partial_E (P(E, t) N(E, t)) - \frac{N(E, t)}{\tau_{esc}(E)} + Q(E, t)$$

The proton distribution $N(E, t)$ depends on a loss term

$P(E,t)$, an escape term $\tau_{esc}(E)$ and a source term $Q(E,t)$. Hereafter we discuss the solutions of the diffuse equation in the simplest case where the losses can be neglected with respect to escape and assuming a time independent injection.

2.1 Injection from the cluster

The cluster injects a distribution of particles at a rate $Q(E,t)$ in the HII region surrounding the cluster. We take $Q(E,t) = Q_0(E/E_0)^{-s} \exp(E/E_{max}(t))$ with $E > E_{inj}$ where E_0 is the reference energy, E_{max} the maximum energy and E_{inj} the injection energy. The spectral index of injection is s . We will consider that a fraction ξ of the wind power is converted in hadron power [15] hence

$$\int dE EQ(E) = \xi \frac{L_w}{V_{bubble}} \quad (1)$$

where V_{bubble} is the volume of the region of the freely flowing stellar wind. Its radius is given by [6].

We have $E_{inj} < E_0 \ll E_{max}$. We assume that we have an efficient acceleration mechanism able to accelerate particles at least in the TeV domain; hence we may have $E_{max} > 100$ TeV. As we are interested in the gamma-ray range E_0 has to be chosen in that energy domain. Considering the possibility for Fermi observations we may select $E_0 = 1$ GeV at the edge of gamma-ray domain observed by Fermi. Neglecting the exponential in the source term one gets for $s > 2$

$$Q_0[\text{part}/\text{cm}^3\text{sGeV}] \simeq \xi \frac{L_w}{V_{bubble} E_0^2} \times \frac{(s-2)}{(E_{inj}/E_0)^{2-s}} \quad (2)$$

This gives the normalization of protons if $E_0 = 1\text{GeV}$ (otherwise the energy unit in Q_0 as to be changed). One can choose E_{inj} close to E_0 : two choices are proposed either $E_{inj} = E_0$ or $E_{inj} = 1/10E_0$.

2.2 Propagation in the HII region

We assume that most of the radiation is produced in the HII region which harbors the highest densities. Although we may well have a contribution from the cluster itself especially from electrons. Once we know the source term $Q(E,t)$ the time dependent solution including escapes is:

$$N(E,t) = \int_{t_0}^t dt' Q(E,t') \exp(-\int_{t'}^t dt''/t_{esc}(t'')) \quad (3)$$

As a basic parametrization the escape time can be written as:

$$t_{esc} = \frac{R_{HII}(t)^2}{6D(E)} \quad (4)$$

where R_{HII} is the HII region radius. The 6 factor means we have 3D diffusion. The spatial diffusion coefficient D can be compared to the standard ISM diffusion value at 3 GeV $D_0 = 4 \times 10^{28} \text{cm}^2/\text{s}$:

$$D = (D/D_0) \times D_0 \times (E/E_i)^{2-\nu} \quad (5)$$

ν is the index of the turbulence $\nu = 2, 5/3, 3/2, 1, 0$ for multiple shocks turbulence, Kolmogorov turbulence, Kraichnan turbulence, Bohm turbulence, microscopic

turbulence with scales \ll Larmor radius. We get:

$$t_{esc} = (120\text{yrs}) R_{HII,10\text{pc}}^2 \times (D_0/D) \times (E/E_i)^{-2+\nu} \quad (6)$$

Under conditions that prevail in massive star clusters and their surrounding HII regions that the escape time is shorter than the loss time scales $t_\pi \sim 5 \times 10^5 \text{ yrs}$ and the age (a few Myrs).

This region as being turbulent could produce a re-acceleration of the particles but the timescale is $t_a = 9D/V_a^2$ and unless the magnetic field being very strong in these regions (more than mG) the Alfvén velocity V_a is small and t_a large with respect to the escape timescale, unless $D/D_0 \sim V_a/c \sim 10^{-5}$. Hence no stochastic acceleration a priori.

Eq.3 cannot be solved analytically, especially if we account for the time dependence of R_{HII} . If one assumes the injection to be stationary and the age $t \gg (t_{esc}, t_0)$ the solution is simple $Q(E)t_{esc}(E) \propto E^{-s-2+\nu}$.

2.3 Gamma-ray flux received on earth

The gamma-ray emissivity is [9]:

$$q_\gamma(\text{ph}/\text{cm}^3\text{sTeV}) \sim 2 \int_{E_{\pi,min}}^{\infty} q_\pi dE_\pi/E_\pi \quad (7)$$

if $E_\gamma, E_\pi \gg m_\pi$. In that limit $E_{\pi,min} = E_\gamma$. The pion emissivity is:

$$q_\pi = \frac{c n_{HII}}{K_\pi} \sigma_{pp}(m_p + E_\pi/K_\pi) N(m_p + E_\pi/K_\pi) \quad (8)$$

$K_\pi = 0.17$ is the mean fraction of the incoming proton imparted into the pion. n_{HII} is the density of the HII region. $N(E)$ is the solution of the diffusion equation. The differential flux received on earth is

$$\phi_\gamma(\text{ph}/\text{cm}^2\text{sTeV}) = V_{HII} q_\gamma(E_\gamma)/(4\pi d^2) \quad (9)$$

where d is the distance of the cluster. V_{HII} is the volume of the HII region.

2.4 Emission from the cluster

A further step would be to link the VHE gamma ray spectrum with the cluster energetics; under the hypothesis of TeV gamma rays produced by particles with energies $E \sim E_{max}$.

It is expected that the particle diffusion is likely to dominate the particle transport and escape in the cluster. For hadrons it is also rather likely that escape dominates losses again. The acceleration mechanism in the cluster needs to be specified.

To summarize, the most relevant parameters to model the gamma-ray emission in the proposed approach are: the stellar winds luminosity, the size of the cavity formed by the stellar winds (region of acceleration), the density and size of the HII region (region supposed to emit gamma rays), the distance and age of the cluster.

3 Sample of star clusters

Here we detail our approach to build a sample of promising clusters for gamma-ray astronomy. We

limited our survey to $\text{Dec} < 20^\circ$ visible at lower zenith angle from the southern hemisphere : H.E.S.S.-II and CTA-south. Astrophysical criteria are detailed as follows.

3.1 Young star clusters

Supernova remnants are already known as gamma-ray emitters. That is why we consider only very young star cluster, to avoid any supernova contribution. For this reason we select clusters containing stars in the main sequence (class V) and also some clusters where the isochrone suggests a star contamination or spread formation episodes. Given that a cluster evolves after some million years, depending on the Initial Mass function, our selection is equivalent to a cut in age. So their age is about a million years.

3.2 Powerful stellar winds

From our model, the normalization of the proton distribution is proportional to the total stellar winds luminosity which is given by :

$$L_w = \sum_{i=1}^{N_*} \frac{1}{2} \dot{M}_i v_{\infty,i}^2$$

where N_* is the number of stars, \dot{M}_i and $v_{\infty,i}$ are the mass-loss and the terminal velocity for the star i . We consider the mass-losses and the terminal velocities as constants. Mass-loss is significant only for O stars [10]. $\dot{M} = \lambda M^\mu$ where :

$$\begin{cases} \lambda = 10^{-8} M_\odot \cdot \text{yr}^{-1} \text{ and } \mu = 1.6 & \text{if } M > 20 M_\odot \\ \lambda = 0 & \text{if } M < 20 M_\odot \end{cases}$$

Our starting point is a catalog of O stars giving their cluster host [11]. We don't take into account the other stars in the cluster but the total stellar winds luminosity is always dominated by the most massive components [10]. For a given spectral type, [12] associates a terminal velocity, and [13] provides a bolometric luminosity. The mass-loss is then calculated by [14] :

$$\left(\frac{\dot{M}}{M_\odot} \right) = 10^{-14.97} \left(\frac{L}{L_\odot} \right)^{1.62} \text{yr}^{-1} \quad (10)$$

4 Identifying the most promising candidates

Our model depends on several parameters. Some of them are constrained by observational data : the size of the interstellar bubble, the size of the HII region, the HII region density, the distance. The stellar winds luminosity is hardly constrained by the spectral type of the stellar content. Some parameters remain to be discussed : E_{inj} , E_0 , E_{max} , ξ , s and ν . Practically we fix $E_0 = 10 E_{inj} = 1 \text{ GeV}$. We choose $E_{max} > 100 \text{ GeV}$ to have a power law in the TeV regime. The parameters ξ , ν and s are crucial for the normalization and the spectral index but remains unconstrained.

So we build a variable Γ given by :

$$\Gamma = \frac{L_w R_{HII}^5 n_{HII}}{R_{bubble}^3 d^2}$$

Assuming that the unconstrained parameters are the same for all clusters. The Γ variable allows us to sort the clusters by their normalization as shown on Table 1 whatever is the efficiency, the turbulence and the spectral index of the injected protons.

Cluster Name	L_w (erg.s ⁻¹)	Γ_{80}
NGC 6604	2.4e+37	9.5e+2
RCW 62 (IC 2944)	1.4e+37	2.4e+1
IC 2177	1.9e+36	1.8e+1
NGC 6193	2.8e+37	8.4e+0
NGC 6523	1.6e+37	7.4e+0
NGC 1976	1.8e+36	8.1e-1
NGC 6618	4.9e+37	1.3e-1
NGC 2244	2e+37	7e-2
NGC 2175	1.9e+36	1.2e-2
NGC 2467	3e+37	6.5e-3
NGC 3324	2.3e+36	6.8e-4
RCW 75	1.5e+35	1.9e-6
RCW 8	5.1e+35	4.2e-7

Tab. 1 – Sample of star clusters sorted by the $\Gamma_{80} = \Gamma/1e80$ parameter. L_w is computed from spectral types of each star in each cluster.

5 Discussion on efficiency and turbulence

Here we probe the turbulence and the efficiency for two cases : NGC 1976 and NGC 2244. Firstly, these objects are promising because of the nice spherical geometry of the bubble and the HII region. Secondly, their bubble size is observationally known which avoid discussions on interstellar bubble models.

The spectral index of the injection is fixed around 2 (2.1 here). This is a conservative assumption which allows us to discuss the spectral index due to the turbulence. Figure 2 shows the expected differential flux on earth. First, this object would be observable with CTA in 50 hours with a efficiency $\xi > 1 \times 10^{-5}$ with $\nu = 5/3$ (Kolmogorov turbulence). Then, for the same turbulence the Fermi-LAT upper limit imposes $\xi < 5 \times 10^{-5}$. In a Kraichnan turbulence case, this upper limit imposes $\xi < 1 \times 10^{-4}$ and puts this object at the limit of the sensitivity of CTA.

The observability of the Orion Nebula (NGC 1976) is hardly constrained by the Fermi-LAT upper limit which imposes the efficiency $\xi < 2 \times 10^{-6}$. Besides we reach here the limit of the CTA sensitivity.

On the whole, the Fermi-LAT data already hardly constrain the parameters under our simple hadronic model. It gives a very low efficiency. This can be interpreted by a very low efficiency of these objects to accelerate hadrons. However, the efficiency can not be compared to the one of a SNR. The latter releases a given amount of kinetic energy during the explosion whose a fraction is converted to accelerate particles. Concerning star clusters, the release of energy is continuous. Moreover we assume a constant stellar wind luminosity which is idealistic and this one should be lower in the early stage of the cluster.

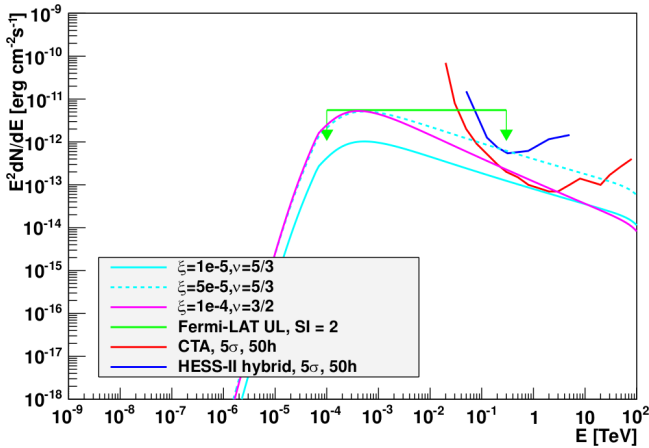


Fig. 1 – Differential flux as a function of the energy for the cluster NGC 2244 associated with the Rosette Nebula. The blue line corresponds to a 5σ sensitivity for a point-like source with 50 hours of observation using the H.E.S.S.-II telescopes in hybrid mode [16]. The red line is the equivalent sensitivity with the CTA [17]. These sensitivities are preliminaries. The green line is the Fermi-LAT upper limit (UL) using the data from the beginning of the experiment to May 2013. The magenta and light blue lines come from our model with different values of ξ and ν .

6 Conclusion

We proposed a new hadronic model of the gamma-ray emission for very young star clusters. A sample of clusters is obtained and sort by the normalization of the predicted gamma-ray flux. Considering a Kolmogorov or Kraichnan turbulences, a very low efficiency is expected for these objects given the Fermi-LAT upper limits. In any cases, IACTs observations could provide a new constraint of these parameters.

To go further, a leptonic model should be investigated and an emission from the cluster it-self as well. A systematic study with IACTs could be relevant to better understand and constrain the possibility of young star clusters to be gamma-ray emitters.

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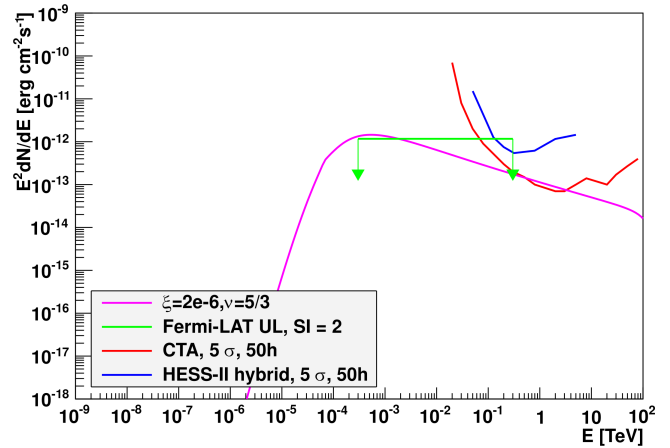


Fig. 2 – Differential flux as a function of the energy for the Trapezium cluster associated with the Orion Nebula (NGC 1976). The blue and red line are the same H.E.S.S.-II and CTA sensitivities as defined before. The green line is the Fermi-LAT upper limit (UL) using the data from the beginning of the experiment to May 2013. The magenta line is given by our model fixing $\xi = 2 \times 10^{-6}$ and $\nu = \frac{5}{3}$.

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