GAMMA-RAY SIGNATURES OF PARTICLE ACCELERATION AT STELLAR WIND TERMINATION SHOCKS UP TO PEV ENERGIES

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Abstract. We model the escape and the transport of cosmic rays (CRs) from stellar wind termination shocks (WTS) to molecular clouds, where proton-proton (p-p) interactions producing γ-rays occur. The goal is to constrain the parameter space enabling a detectable excess in the γ-ray flux up to hundreds of TeV, and the corresponding subset of systems star cluster/cloud. Then the perspective is to find real such systems and compare predictions of the models to data in order to infer the values of several parameters, such as the WTS efficiency, the diffusion coefficient or the injection slope. Another application is to try to explain some of the unidentified LHAASO Ultra high energy (UHE) γ-ray sources and "dark PeVatrons" with these kinds of systems.

Keywords: transport, acceleration, gamma-rays, molecular clouds.

1 Introduction

One of the main phenomenon that is not yet well understood in galactic CR physics is how CR protons can be accelerated to the knee (~ 1 PeV) and up to 100 PeV. The standard SNR paradigm cannot answer this question in an unanimous way (Gabici et al. 2019) and therefore other classes of sources, such as star clusters, have been explored in the last few years (Aharonian et al. 2019). And now, thanks to the new LHAASO UHE γ-ray data, it should be possible to determine which source can accelerate protons up to PeV energies (if we find a source where leptonic emission can be excluded). Indeed, by comparing an observed UHE γ-ray flux with the predicted flux generated by different accelerators through p-p interactions, we could identify which source best fits the data and therefore which source is more likely to accelerate protons up to PeV energies. For this best fitting source, it also enables to infer interesting parameters like the injection slope, the CR acceleration efficiency, or the diffusion coefficient (Gabici et al. 2010). Here, we constrain the parameter space for which a system star cluster/cloud could create a detectable excess in the γ-ray flux up to hundreds of TeV.

2 Cosmic ray transport model

Star clusters are continuous accelerators for which particles and energy are diluted over a much longer timescale than impulsive sources such as SNRs (that inject a very big amount of particles and energy in a short amount of time). But in both cases, at some point the accelerated particles will escape the source and be transported in the ISM. They can then reach a dense molecular cloud, and hit target protons, therefore producing signature γ-rays via π^0 decay (Gabici et al. 2007).

We want to determine the maximal distance between the accelerator and the molecular cloud that can enable a detectable excess of γ-rays up to hundreds of TeV. Of course this depends on several parameters of the transport model. We consider a 3D isotropic diffusion model with point-like sources. Noting $f(E, R, t)$ the particle distribution function of protons with energy E, at time t after the start of the injection, and at distance R from the source, the transport equation is the following one:

$$\frac{\partial f}{\partial t} = \frac{D(E)}{R^2}\frac{\partial}{\partial R}(R^2\frac{\partial f}{\partial R}) + \frac{\partial}{\partial E}(\frac{E}{\tau_{pp}}f) + S(E, R, t) \tag{2.1}$$

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with τ_{pp} the protons lifetime, $D(E) = D_0(\frac{E}{10 \text{ GeV}})^\delta$ the diffusion coefficient, and $S(E,R,t) = Q_0\delta(R)E^{-\alpha}\exp\left(-\frac{E}{E_{max}}\right)$ the injection term for continuous source, considered here as a point-like WTS, where we take $E_{max} = 3$ PeV.

Outside clouds the proton density is small ($n \leq 10cm^{-3}$) therefore, noting t_{age} the age of the cluster, $\tau_{pp} \sim 6 \cdot 10^7(\frac{n}{1cm^{-3}})^{-1}\text{yr} > \text{t}_{\text{age}}$ and the energy loss term can be neglected. The solution of this equation is then given in Aharonian & Atoyan (1996):

$$f(E,R,t) \simeq \frac{Q_0}{4\pi D(E)R}E^{-\alpha}erfc\left(\frac{R}{R_{diff}(E,t)}\right)\exp\left(-\frac{E}{E_{max}}\right) \tag{2.2}$$

where $R_{diff} \sim \sqrt{4D(E)t}$ is the diffusion radius and $erfc$ the complementary error function.

The normalisation Q_0 is computed such that $\epsilon L_w = \int_{E_{min}=m_pc^2}^{E_{max}} dE_{tot}Q_0E_{tot}^{-\alpha}E$, with L_w the mechanical wind luminosity and ϵ the CR acceleration efficiency, which gives $Q_0 \sim \epsilon L_w(\alpha-1)(\alpha-2)(m_pc^2)^{\alpha-2}$.
L_w will be computed from stellar cluster population simulations, and we will take $\epsilon = 10\%$, but we want to constrain the ratio ϵ/D_0. Moreover, the time will be taken as the age of the considered cluster (around Myr) and therefore the time dependence will be negligible since we will have $R_{diff} \gg R$.

A model taking into account the spatial extensions of the cloud and of the cluster, based on the work of Li & Chen (2010), will also be considered in the future. Moreover, models with advection (Morlino et al. 2021) or with anisotropic 1D diffusion parallel to magnetic field lines (Nava & Gabici 2013) are currently under study.

Now, to know for which maximal distance to the source it will be possible to have an excess of CRs compared to the background (and then of γ-rays if we have p-p interactions), we have to model the CR sea. We consider this very simple form on a broad energy range:

$$E^2 n_{CR,bcg}(E) = 0.6\left(\frac{E}{m_pc^2}\right)^{-0.7} \text{eV cm}^{-3} \tag{2.3}$$

This enables to obtain an analytic estimation for the maximal distance allowing for an excess. Indeed, neglecting the term $erfc(\frac{R}{R_{dif}})$ in eq. 2.2 (therefore supposing $R_{diff} >> R$, which can be verified a posteriori), an excess of CRs is possible if $n_{CR,wind}(E,R,t) > n_{CR,bcg}(E)$, that rewrites in:

$$R < E^2\frac{Q_0E^{-\alpha}}{4\pi D(E)n_{CR,bcg}(E)}\exp\left(-\frac{E}{E_{max}}\right) \tag{2.4}$$

$$R_{max} \approx 3 \times 10^2\,(\alpha-1)\,(\alpha-2)\left(\frac{\epsilon L_w}{10^{38}\text{erg/s}}\right)\left(\frac{10^{28}\text{cm}^2/\text{s}}{D_0}\right)\left(\frac{E}{m_pc^2}\right)^{2.7-\alpha-\delta}\exp\left(-\frac{E}{E_{max}}\right)\text{ pc} \tag{2.5}$$

We consider for instance $\delta = 0.5$, $\alpha = 2.2$, $D_0 = 10^{28}$ cm^{2}s^{-1}, and $L_w = 5 \cdot 10^{38}$ erg/s. At $E = 10$ GeV, this gives $R_{max} \sim 36$ pc and at $E = 3$ PeV, this gives $R_{max} \sim 13$ pc.

3 Excess seen in gamma-rays

From the proton spectrum in eq. 2.2 we can get the γ-ray emissivity q_γ coming from the p-p interactions between the accelerated protons and the target protons in a molecular cloud of mass $M_\odot$ and at distance d from Earth. We use the parametrization from Kafexhiu et al. (2014) and can then convert the emissivity into a γ ray flux :

$$q_\gamma = 4\pi n_H\int\frac{d\sigma}{dE_\gamma}(T_p,E_\gamma)J(T_p)dT_p \tag{3.1}$$

$$\phi_\gamma = \frac{q_\gamma}{n_H 4\pi d^2}\frac{M_{cloud}}{m_p} \tag{3.2}$$

In the same way, with eq. 2.3 we can obtain the γ ray flux coming from the interaction between the CR sea and the molecular cloud. To obtain the total γ ray background along the line of sight, we must also take into account the interaction of CRs with diffuse gas and therefore multiply by $(n_{col}^C + n_{col}^D)/n_{col}^C$ with n_{col}^C the column density of the molecular cloud and n_{col}^D the column density of the diffuse gas in the target region.

We can also compute the total γ ray background along the line of sight from direct observations. Indeed, taking LHAASO diffuse background (Cao & Lhaaso Collaboration 2023) and Fermi-LAT diffuse background (Orlando 2018) in the line of sight of the considered cloud (so multiplied by $\pi\theta_{cloud}^2$), we obtain the total γ ray flux by multiplying this time by $(n_{col}^C + n_{col}^D)/n_{col}^D)$. We get less than a factor 2 difference from the previous method, and will only plot the background obtained with the first method in the following.

We also consider the point-like sensitivities of several γ -ray detectors (Fermi-LAT,LHAASO,CTA). The extended sensitivity would be obtained by multiplying the point-like sensitivity by a factor $\theta_{cloud}/\theta_{res}(E)$ with θ_{cloud} the angular size of the cloud and and $\theta_{res}(E)$ the angular resolution of the considered detector, at energy E.

4 Results

We can now plot the γ-ray flux against the distance between the cluster and the cloud, at different fixed energies and for several sets of parameters. We consider $L_w = 3 \cdot 10^{38}$ erg.s^{-1} (similar to Cygnus OB2 's one). Moreover, we take as an example a molecular cloud of $10^5 M_\odot$ and located at 1kpc from Earth.
We also plot at these energies the background at this cloud, and the point-like sensitivity of the detectors (Fermi-LAT for 1GeV, LHAASO for 300TeV).

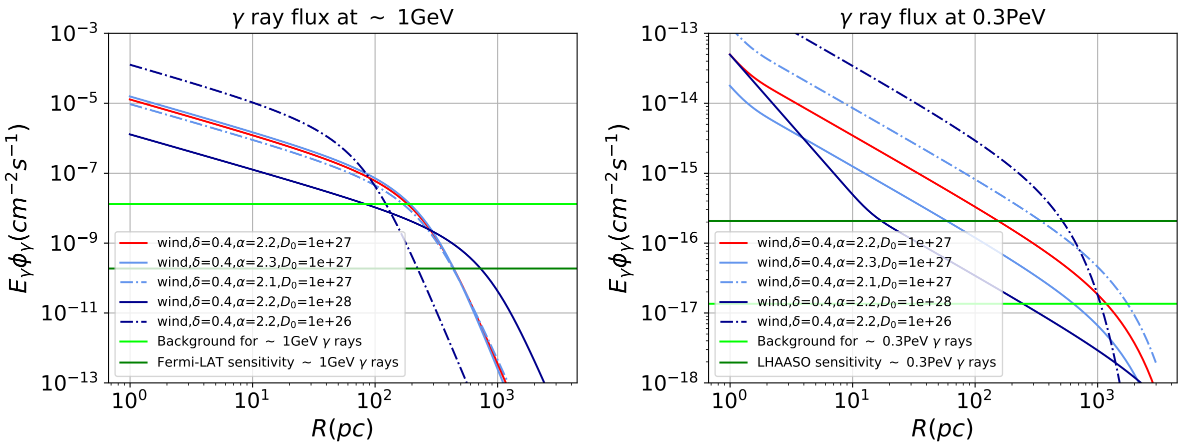

Fig. 1. Left: γ-ray flux at 1GeV for a star cluster of mechanical luminosity $L_w = 3 \cdot 10^{38}$ erg/s and a molecular cloud of $10^5 M_\odot$ at 1kpc. **Right:** γ-ray flux at 300TeV for a star cluster of mechanical luminosity $L_w = 3 \cdot 10^{38}$ erg/s and a molecular cloud of $10^5 M_\odot$ at 1kpc. At small distances, the diffusion regime is not valid anymore since the situation corresponds to very recent times ($t < \frac{3D(E)}{c^2}$) and applying the diffusion regime would violate the speed of light. Instead, we have to consider the ballistic regime (where $f \sim 1/R^2$ instead of $f \sim 1/R$ in the diffusion regime)

At lower energies ($\sim$ 1 GeV) we can see several characteristics. First, every γ-ray excess above the background can be seen (the light green curve is above the dark green one). Then, the maximal distance does not highly depend on parameters (diffusion and injection) and is around 100pc for a luminosity of $3 \cdot 10^{38}$ erg/s and a cloud of $10^5 M_\odot$ at 1kpc from Earth.

On the contrary, at higher energies ($\sim$ 300 TeV) we have different properties. Indeed, we can have excesses that cannot be seen by detectors (LHAASO here): this corresponds to the curves that are above the light green curve but below the dark green one. Thus, we have an effective maximal distance to have a detectable excess, that highly depends on diffusion and injection parameters, and is also around 100pc for a luminosity of $3 \cdot 10^{38} erg/s$ and a cloud of $10^5 M_\odot$ at 1kpc from Earth, but can be as high as 500pc and as low as 10pc.

To have a more complete view of the situation and see the energy dependence, we can plot the γ-ray flux spectra (flux against energy), fixing a distance taken for instance as 50pc. We also show the point-like differential sensitivities of several γ-ray detectors (LHAASO,CTA North, Fermi-LAT):

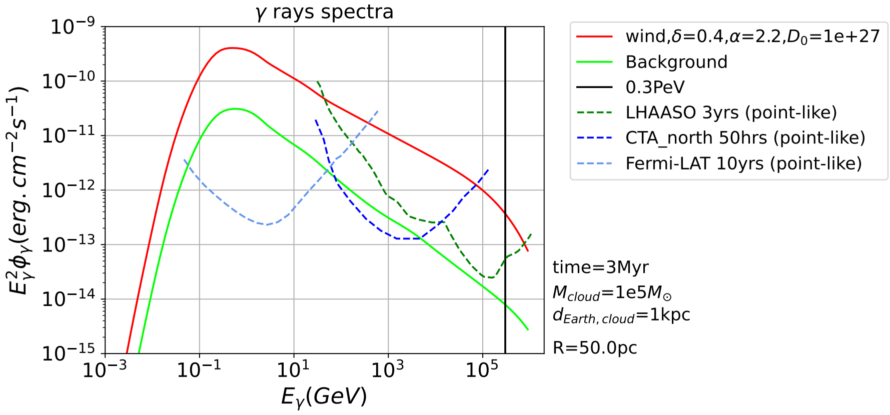

Fig. 2. γ-ray spectra from the background (light green curve) and from the source (red curve) for a given set of parameters, especially $L_w = 3 \cdot 10^{38}$ erg/s and $D_0 = 10^{27}\text{cm}^2/\text{s}$, therefore supposing a suppression of diffusion coefficient compared to the galactic one, typically via streaming instabilities. There is an excess in the whole energy range here and it can be seen by the instruments whenever the red curve is above the corresponding dashed curve.

By varying parameters and plotting these kinds of spectra, we can explore and constrain the parameter space to find the configurations that enable detectable excess in the desired energy range, and the corresponding systems star cluster/cloud. Moreover, when we detect a γ-ray source that can correspond to this physical situation, we can try to fit this theoretical spectrum with the observed one and infer several parameters of the model (mainly the injection slope and the ratio ϵ/D_0).

An application to a recent UHE source detected by LHAASO in the W43 region is currently under study.

5 Conclusion

In this work, we modeled the transport of CRs from a continuous accelerator such as a star cluster to a molecular cloud where γ-rays can be created via p-p interactions. We studied the parameter space in which an excess of γ-rays can be seen on Earth, and mainly the distance between the star cluster and the cloud. We saw that at very high energies we have an effective maximal distance to detect the excess, and that the resulting flux is much more sensitive to a change of parameters than at lower energies.
We now want to apply this on real systems, and try to compare the predicted flux to observed ones, thus infering parameters of the model (mainly the injection slope and the ratio ϵ/D_0).

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