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Modeling gamma-ray signatures of particle acceleration in stellar clusters from GeV to PeV

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A couple of classes of astrophysical objects such as young massive stellar clusters (YMSCs) have recently emerged as promising galactic PeVatron candidates, potentially explaining the knee of the cosmic-ray spectrum as alternative to isolated supernova remnants (SNRs). Meanwhile, the LHAASO observatory is the first to effectively probe the photon detection band above 0.1 PeV, that can correspond to multi-PeV hadronic cosmic rays. Thus, it enables the use of its gamma-ray data, combined to other complementary detectors such as HESS or Fermi-LAT, to constrain galactic particle acceleration models and parameters. It can also help for trying to identify the contribution from the different categories of galactic accelerators to the observed cosmic ray flux, especially towards the PeV domain.

In this context, we model the escape and transport of cosmic rays from their acceleration site to nearby molecular clouds or clumps, where proton-proton interactions producing high-energy gamma rays occur. Our focus is on scenarios where the source is a YMSC, with particles being accelerated at shocks (either wind termination shocks or embedded SNRs) before escaping into the interstellar medium. Using a semi-analytical approach, we explore the conditions (e.g., source-cloud distance, time, injection slope, number of stars) required to produce a gamma-ray excess above the sensitivity of the detectors. This allows us to identify the parameter space where such a signal could be observed and, consequently, to determine which cluster-cloud systems are viable candidates for producing such an excess. Finally, we compare model predictions with gamma-ray data to refine key acceleration parameters, such as the wind termination shock efficiency or the injection spectrum. Additionally, we investigate whether some of the so-called dark PeVatrons detected by LHAASO could be explained by star cluster–cloud systems.

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