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Are T Tauri stars gamma-ray emitters? Insights from a non-thermal model

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Abstract. T Tauri stars, due to strong magnetic activity, are potential sites for non-thermal emission via magnetic reconnection events. Recently, high energy radiation was detected using *Fermi*-LAT in a star-forming region and associated with flares from a T Tauri star. Motivated by this, we developed a radiative model to constrain the physical parameters of the source. We considered a scenario where particles are accelerated locally in magnetic loops during flares. First we calculated the relevant time scales and determined the main emission mechanisms: synchrotron and proton-proton interaction, for electrons and protons respectively. Subsequently, we calculated the maximum energy reached by the particles and attested the hadronic origin of the emission. Additionally, we compared the reported and modeled spectral energy distribution using both stationary and time-dependent models, proposing two explanations for the observed behavior: absorption through the $\gamma-\gamma$ annihilation process (E_{ph} = 87 eV) and generation of particles with a harder spectral index. Finally, we discussed the detectability for the *Cherenkov Telescope Array Observatory* and the ASTRI *Mini-array*.

Resumo. Estrelas T Tauri, devido à intensa atividade magnética, são fontes potenciais para emissão não térmica através de eventos de reconexão magnética. Recentemente, radiação de altas energias foi detectada utilizando o *Fermi*-LAT em uma região de formação estelar e associada à *flares* de uma estrela T Tauri. Desse modo, desenvolvemos um modelo radiativo para restringir os parâmetros físicos da fonte. Consideramos um cenário em que partículas são aceleradas localmente em *loops* magnéticos durantes *flares*. Primeiro, calculamos as escalas de tempo relevantes e determinados os principais mecanismos de emissão: síncrotron e interação próton-próton, para elétrons e prótons respectivamente. Além disso, calculamos a energia máxima alcançada pelas partículas e atestamos a origem hadrônica da emissão. Ademais, comparamos a distribuição espectral de energia reportada com a obtida com um modelo estacionário e outro dependente do tempo. Propusemos duas explicações para o comportamento observado: absorção através do processo de aniquilação $\gamma-\gamma$ (E_{ph} = 87 eV) e a geração das partículas com um índice espectral duro. Por fim, discutimos sobre a detectabilidade para o *Cherenkov Telescope Array Observatory* e para o ASTRI *Mini-array*.

Keywords. Gamma rays: stars – Stars: variables: T Tauri, Herbig Ae/Be – Acceleration of particles

1. Introduction

T Tauri stars are protostars that present intense magnetic activity. The magnetic field lines from the star reconnect with each other and also with the accretion disk lines, releasing the stored energy in magnetic reconnection events during flares similar to those observed in the Sun. This mechanism could accelerate particles to relativistic energies, producing a population of particles that interact with the medium, emitting high energy radiation, see del Valle et al. (2011). Recently, Filócomo et al. (2023) associated a Fermi source (2FGL J0547.1+0020c) to a T Tauri star in the stellar-forming region NGC 2071.

In this work, we considered the model from del Valle et al. (2011) with the *Fermi*-LAT detection as a reference, establishing if T Tauri are transient gamma-ray sources. We started by calculating the time scales involved in the radiative processes, following del Valle et al. (2011). Then, we developed two models to study the spectral energy distribution (SED): stationary and time-dependent.

In the stationary case, we inferred a peculiar behavior of the source and raised two hypotheses to explain it. For the time-dependent model we fitted the observed data with the modeled spectrum. Finally, we compared the time-dependent SED with the *Cherenkov Telescope Array Observatory* (CTA) and the ASTRI *Mini-array* sensitivity curves to determine if these events are detectable with the next generation Cherenkov observatories.

2. Acceleration and Radiative Model

We assume that particles are accelerated locally in magnetic reconnection events between the magnetic field lines of the T Tauri star and its accretion disk, producing flares. Our model follows what is proposed in del Valle et al. (2011). To calculate the proton-proton interaction emission we used the `NAIMA` (Zabalza 2015) package.

2.1. Time Scales

Firstly, we calculated the time scales involved in the acceleration of electrons and protons. Therefore, for leptons and hadrons we considered the acceleration and convection rate. For the radiative losses we estimated the synchrotron, inverse Compton and relativistic Bremsstrahlung for electrons and proton-proton (pp) interaction for protons. For a detailed description of the parameters used as well as the time scales see Capellini & del Valle (2024).

The acceleration time scale was calculated according to the following equation:

$$t_{acc} = \frac{E}{eB\eta c}. \quad (1)$$

Through this calculation we determined that the main emission mechanisms are synchrotron for leptons and pp for hadrons. Equating the energy gains with the main energy loss we obtained that the maximum energy reached by electrons is $E_{e,max}$ = 1 GeV while for protons is $E_{p,max}$ = 10 TeV. Additionally, we verified that $E_{e,max}$ is lower than the reported detection even with a magnetic field two orders of magnitude greater. Therefore, we attested that the emission has a hadronic origin and the modeled SED considers only the hadronic interaction.

2.2. Stationary Model

The SED from the source 2FGL J0547.1+0020c, reported in Filócomo et al. (2023), consists of a detection only at the energies $\sim 10^{11}$ eV, and upper limits at the lowest energy bins. This lack of observed flux is peculiar. To explain it, we proposed two hypotheses: generation of particles with harder spectral index and $\gamma - \gamma$ annihilation.

Thus, to analyze the first hypothesis we considered a power law for the particle distribution function ($N(E) \propto E^{-p}$) and fitted the SED from the pp process varying the spectral index from 0.8 to 2.0. Our best visual fit was obtained for $0.8 \leq p \leq 1.0$. For the $\gamma - \gamma$ annihilation process, we calculated the energy of the photon target field for which we have a maximum absorption in the low energy region. We obtained that this maximization condition occurs for E_{ph} = 87 eV, and , therefore, could be from the synchrotron emission. For a detailed explanation see Capellini & del Valle (2024).

2.3. Time-dependent Model

In the time-dependent case we calculated the particle energy distribution, $N(E,t)$, using the finite differences method to solve the transport equation $\partial_t N = \partial_E(PE) - \frac{N}{\tau_{esc}} + Q$, where P is the losses factor, τ_{esc} is the escape time scale and $Q := Q_0 E^{-1} e^{-E/E_0} e^{-t/t_{max}}$ is the particle injection, with E_0 as the particle's maximum energy and t_{max} as the injection's maximum time. Once we obtained the particle distribution function, we calculated the SED from the pp process considering the distance $d = 390$ pc and compared with the *Fermi* data. The result shown in Figure 1 suggests that the data can be fitted with the proposed model.

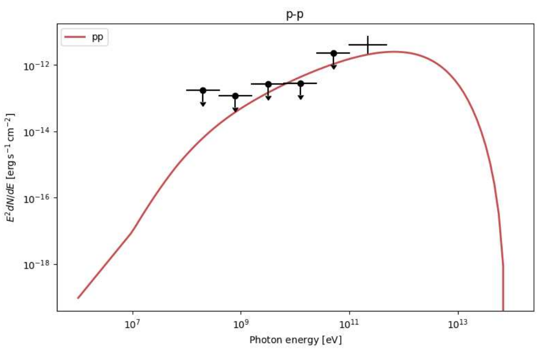

Figure 1. SED calculated considering the pp process compared with the reported Fermi emission associated with a T Tauri star in the star forming region NGC 2071.

3. Detectability

The *Fermi*-LAT detection was associated with a T Tauri star in the star-forming region NGC 2071. Considering the SED calculated from the time-dependent model, we compared the emission with the sensitivity curves of CTA and ASTRI *Mini-array*. Figure 2 shows that this flare event from a T Tauri star could be detected with the next generation Cherenkov observatories.

4. Discussion & Conclusions

In this work we used the model from del Valle et al. (2011) in order to verify if T Tauri stars can explain the Fermi source 2FGL J0547.1+0020c, as suggested by Filócomo et al. (2023). We started our analysis calculating the time scales for the relevant radiative processes and the SED for a stationary and a time-dependent model.

From the timescales we determined that the emission is hadronic and that the maximum energy reached by protons is 10 TeV. Using the stationary model we investigated the peculiar SED reported raising the possibility of a harder generation of particles ($0.8 \leq \alpha \leq 1.0$) or an absorption mechanism for a photon target field with E_{ph} = 87 that could be from the synchrotron emission. For the time-dependent model, we calculated the SED solving the transport equation and fitted with the data.

We conclude that T Tauri stars are transient gamma-ray emitters. Moreover, assuming the flare scenario of this work, the high-energy emission from these protostars is above the sensitivity flux predicted for CTA and might be detected with the next generation Cherenkov observatories.

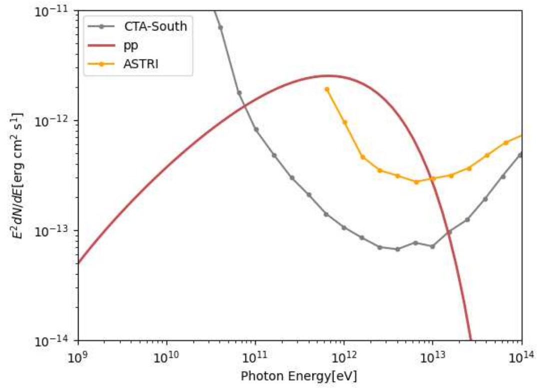

Figure 2. Detectability analysis by comparing the emission curve (red) with the CTA (grey) and the Astri *Mini-array* (yellow) sensitivity curves- data from (Cherenkov Telescope Array 2021) and (ASTRI Project 2022).

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