Boletim da Sociedade Astronômica Brasileira, **36**, no. 1, 202-203

T Tauri stars as transient gamma-ray sources

G. C. Capellini[1] & M.V. del Valle[1]

[1] Instituto de Astronomia, Geofísica e Ciências Atmosféricas da Universidade de São Paulo - IAG/USP
e-mail: gabriel.capellini@usp.br, mvdelvalle@usp.br

Abstract. T Tauri stars present intense magnetic activity, which makes them favorable sites for events of magnetic reconnection. These events are related to the acceleration of particles to relativistic energies that, consequently, interact with the fields from the environment, producing non-thermal emission. Considering this scenario, we modelled the gamma-ray emission detected with *Fermi*-LAT from the star forming region NGC 2071 in order to verify if T Tauri stars can be responsible for the observed high-energy radiation. Firstly, we studied which objects belong to the region observed by *Fermi*-LAT and concluded that there are 535 astrophysical sources from 30 different classes. Then, we compared the typical time-scales of the processes involved in the acceleration, convection and emission to determine which mechanisms are relevant and the maximum energy reached by the particles. As a result, we infered that the main emission process for electrons and protons are synchrotron and proton-proton interaction, respectively. The estimated maximum energies for electrons and protons are $E^{elec}_{max} \approx 1$ GeV and $E^{prot}_{max} \approx 10$ TeV. After this, we analyzed the spectrum energy distribution from the source and explored two hypothesis to explain its peculiar behaviour: absorption by $\gamma-\gamma$ annihilation from a photon field of $E = 87$ eV, possibly from the synchrotron emission or thermal X-rays from the associated flare and the generation of particles with a harder spectral index, around 0.8 – 1.0. Finnaly, we concluded that T Tauri stars can be gamma-ray sources.

Resumo. Estrelas T Tauri apresentam intensa atividade magnética, o que torna-as fontes favoráveis à eventos de reconexão magnética. Estes eventos estão relacionados à aceleração de partículas até energias relativísticas que, consequentemente, interagem com os campos do ambiente, produzindo emissão não térmica. Tendo em vista este cenário, modelamos a emissão de raios gama detectada com o *Fermi*-LAT da região de formação estelar NGC 2071 com o objetivo de verificar se estrelas T Tauri podem ser responsáveis pela radiação de alta energia observada. Primeiramente, estudamos quais objetos pertencem à região observada pelo *Fermi*-LAT e concluímos que existem 535 fontes de 30 classes distintas. Em seguida, comparamos as escalas de tempo típicas dos processos envolvidos na aceleração, convecção e emissão para obter quais mecanismos são relevantes além da energia máxima alcançada pelas partículas. Como resultado, inferimos que os principais processos para elétrons e prótons são síncrotron e interação próton-próton, respectivamente. Já as energias máximas estimadas foram $E^{elec}_{max} \approx 1$ GeV e $E^{prot}_{max} \approx 10$ TeV. Depois, analisamos a distribuição espectral de energia da fonte e exploramos duas hipóteses para explicar o seu comportamento peculiar: absorção pelo mecanismo de aniquilação $\gamma - \gamma$ graças à um campo de fótons de $E = 87$ eV, possivelmente proveniente da emissão síncrotron ou de raios-X térmicos dos *flares* associados e a geração de partículas com um índice espectral duro, por volta de 0.8 – 1.0. Por fim, concluímos que estrelas T Tauri podem ser fontes de raios gama.

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

1. Introduction

T Tauri stars are young, pre-main-sequence stars that still have an accretion disk. These protostars present strong magnetic activity such as magnetic reconnection. Magnetic reconnection is one of the favorite mechanisms to efficiently accelerate particles to relativistic energies and, consequently, these particles produce high energy non-thermal emission. The possibility of T Tauri stars being gamma-ray sources was first introduced by del Valle et al. (2011) and recently Filócomo et al. (2023) detected gamma-ray emission from the star forming region NGC 2071 using *Fermi*-LAT archive data and attributed this observation to a T Tauri star.

In this research, we aimed to stablish whether T Tauri stars are transient gamma-ray sources, with the observation from the NGC 2071 region as a reference. With this goal, in the next Section we analyzed the known objects inside the error ellipse of the Fermi source. In Section 3 we present the model developed to compute the high energy emission produced. In addition, we studied the spectrum energy distribution (SED). Finally, in Section 4, we show our conclusions.

2. The Detection Region

In order to verify which objects lie inside the detection region from the *Fermi*-LAT source of interest, we considered a 13 arcmin radii circle. This circle encompass the 3-σ significance elipse of the source, centered at 2FGL J0547.1+0020c (RA = 86°.799507, Dec. = 0°.33487). Using a scrip in R, we plotted the objects with their respective classes, totalizing 535 sources from 30 different types. The data was obtained from the SIMBAD database, Wenger et al. (2000).

3. The Model

3.1. Time Scales

To better understand the origin of the emission, we calculated the typical time scales of the event for eletrons and protons. Hence, we considered the acceleration, convection, the time frame of the observation, synchrotron, inverse Compton and relativistic Bremsstrahlung emission, for eletrons, and proton-proton interactions for protons. The parameters of the source assumed were a density $n = 5 \times 10^{11}$ cm^{-3}, a magnetic field $B = 200$ G, a flux tube length $l = 10^{11}$ cm, wind velocity $v_w = 2 \times 10^7$ cm s^{-1}, energy density of target the photon field $u_\epsilon = 3.79 \times 10^{-13}$ erg cm^{-3} and photon energy $\epsilon = 9 \times 10^{-4}$ erg.

Based on these calculation, we conclude that the main mechanisms and the maximum energy reached by the particles are synchrotron with $E_{max} \approx 1$ GeV, for electrons, and proton-proton interactions with $E_{max} \approx 10$ TeV, for protons. The results for protons are shown in Figure 1.

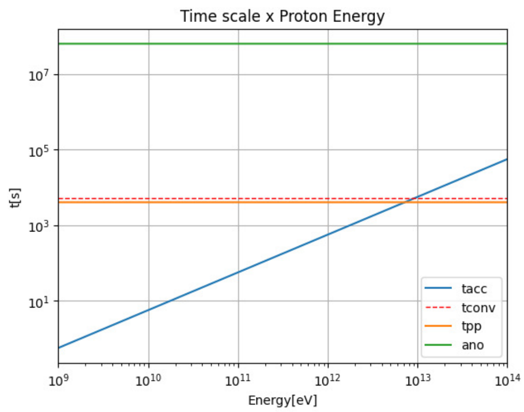

Figure 1. Time scale as a function of energy for protons considering the following mechanisms: acceleration (solid blue), convection (dashed red), 2 year time frame (solid green), proton-proton interaction (solid orange).

With the adopted parameters, the maximum energy reached by the electrons is not sufficient to explain the SED reported by Filócomo et al. (2023) that reaches 300 GeV. Balancing the synchrotron loses with the acceleration time, we obtained a relation between the electron maximum energy and the magnetic field:

$$E = \sqrt{\frac{1}{500}\frac{ec^2}{\sigma_T}\frac{m_e^2}{m_p}\frac{B}{n}}, \tag{1}$$

where e is the electron charge, c is the speed of light, σ_T is the Thomson cross-section, m_e is the electron mass, m_p is the proton mass.

From Equation 1, we concluded that the emission must be hadronic, since even with a magnetic field 100 times greater the maximum energy of the electrons is not sufficient to explain the reported SED.

3.2. Spectrum energy distribution

The spectrum reported by Filócomo et al. (2023) has a peculiar behaviour due to a lack of flux at lower energies. To explain this, we considered the cross-section from the $\gamma - \gamma$ annihilation mechanism (Equation 2) and inferred the energy of the target photon field for which the maximum interaction is reached.

$$\sigma_{\gamma\gamma} = \frac{\pi r_e^2}{2}(1-\beta^2)\left[2\beta(\beta^2-2) + (3-\beta^4)\ln\left(\frac{1+\beta}{1-\beta}\right)\right], \tag{2}$$

where r_e is the classic electron radius, $\beta = \left[1 - \frac{(m_e c^2)^2}{E_\gamma \epsilon}\right]^{1/2}$, with E_γ being the energy of the photon with higher energy in the collision, fixed at 10 GeV, ϵ is the energy of the photon with lower energy.

The target photon must have an energy approximately $\epsilon = 87$ eV. A photon field at these energies can come from the shyncrotron emission from the high-energy electrons or from thermal X-rays from the star.

Another possibility to explain the reported SED is the generation of particles with harder spectral index. Adopting a power-law for the particle distribution (i.e $N \propto E^{-\alpha}$), we calculated the SED varying the spectral index from 0.8 to 2.0. Then, we visually fitted the observed data. From Figure 2 we can deduce that the best fit is obtained with $\alpha = 0.8 - 1.0$, which is a hard spectral index when compared to the canonical $\alpha = 2.0$. This calculation were performed using the NAIMA package, Zabalza V. (2015)

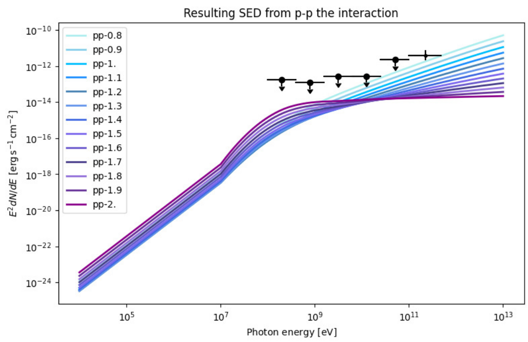

Figure 2. SED obtained with the NAIMA package, Zabalza V. (2015), varying the particles spectral index from 0.8 to 2.0 and visually fitting the data.

4. Conclusions

In relation to the detection region we can conclude that it has a high number of objects (535 sources) with a great diversity (30 classes). Regarding the time scales and the origin of the observed emission, we found that the main mechanisms and their respective maximum energy reached are synchrotron, for electrons ($E_{max}^{elec} \approx 1$ GeV), and proton-proton interactions, for protons ($E_{max}^{prot} \approx 10$ TeV). Because of the low maximum energy reached by the electrons, even with a magnetic field 100 times greater, we can claim that the emission is hadronic.

Despite this fact, the synchrotron emission from electrons, as well as the thermal X-rays from the associated flare, might pose an important role in the absorption of the proton emission due to the γ−γ annihilation. This absorption might be the reason behind the peculiar behaviour of the reported SED. Another possibility is that the emitting have a spectral index around 0.8 – 1.0.

Finally, we conclude that T Tauri stars can be transient gamma-ray sources. Understanding how the emission is produces helps to search and to identify these sources in the high energy data.

Acknowledgements. We thank FAPESP for the support under the processes 2022/16530-8 and 2019/05757-9

References

del Valle, M.V., Romero, G. E., Luque-Escamilla P. L., Marí, J. & Ramón Sánchez-Sutil, J. 2011, Revista Ciência Hoje, 282, 2011, The Astrophysical Journal, 738, 115.

Filócomo, A., Albacete-Colombo J. F., Mestre E., Pellizza L. J. & Combi J. A., 2023, Monthly Notices of the Royal Astronomical Society, 525, 1726

Wenger, M., Ochsenbein, F., Egret, D., Dubois, P., Bonnarel, F., Borde, S., Genova, F., Jasniewicz, G., Lalöe, S., Lesteven, S. & Monier R., 2000, 143, 9

Zabalza V., 2015, 2015, 922