Gamma-ray emission from the microquasar Cygnus X-3

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Abstract: Cygnus X-3 is a microquasar studied over the wide range of electromagnetic spectrum. It is believed to be a powerful source of cosmic rays particles in our galaxy. Gamma-ray emission has also been detected from it in several occasions. Studying gamma-ray emission from Cygnus X-3 will help to understand the process where charged particles are accelerated and gamma-rays formed. We have analyzed data from the NASA's Fermi satellite in two periods of time by performing lightcurves with the aperture photometry analysis. In the first period, from 2008 to 2009, we compare our results with the ones already reported by Fermi LAT collaboration in 2009. In the second period, we analyse recent data from September 2018 to November 2019 following the same criteria and trying to find a period of high activity in gamma-ray emission. Our results corroborate the period of high activity in gamma-rays from June to August 2009 and they show hints of an active period from March to July 2019 where there is a large probability that the high energy gamma-ray emission detected is coming from the source.

I. INTRODUCTION

It is well established that several binary stars are high energy (HE) (0.1-100 GeV) and very high energy (VHE) ($\geq 100GeV$) gamma-rays emitters [1].

X-ray binaries are a subtype of binary stars that are detected in X-rays wavelengths. They are compounded by a compact object, either a black hole or a neutron star, and a companion star. When the donor, the companion star, transfers mass to the accretor, the compact object, gravitational potential energy is released as X-rays.

Microquasars are X-ray binaries displaying a relativistic radio jet. Unlike quasars the black hole is just a few solar masses and the radius of the events is about 100 km. Microquasars are named after the analogy between their black-holes and supermassive black holes in Active Galactic Nuclei which also display relativistic jets. The main advantage of studying them rather than quasars is that the time scale in which processes happen is relatively small. The companion star ejects matter forming an accretion disk around the compact object and part of the energy released is used to launch two streams of fluid and gas of plasma, called jets. These jets contain relativistic particles and non-thermal emission can be detected from them in different wavelengths bands. They spend most of the time in low accretion periods in gamma-rays, with flaring periods that last from days to months. At the time of writing this article, two microquasars have been detected emitting in gamma-rays: Cyg X-3 and Cyg X-1 [2].

Synchrotron radiation occurs when relativistic charged particles, typically electrons, move through magnetic fields. Electrons are always changing their direction spirally. Hence, they will emit photons with energies that depend on the speed of the electron. This electromagnetic radiation is polarized in the plane perpendicular to the magnetic field and it is commonly observed in the radio band although it can also be detected in visible, UV and X-ray wavelengths.

Cygnus X-3, discovered by Giacconi et al. (1967), is a microquasar located in the Galactic plane at a distance about 7 kpc from us with a 4.8 hour orbital period. It is one of the brightest Galactic radio sources and major flares with fluxes reaching 20 Jy are being detected irregularly [3]. Cygnus X-3 is not optically observed because it is obscured by the interstellar dust. The infrared shows that the companion star is a Wolf-Rayet star, called V1521 Cyg. A Wolf-Rayet star is more massive and hotter than almost all the other stars. It presents strong stellar winds that cause large mass losses. V1521 Cyg has a luminosity of 10^{39} erg/s and loses mass at the rate of 10^{-5}solar masses/year [1]. Cygnus X-3 is the only microquasar with these characteristics known in our Galaxy. We differentiate two states in its X-spectrum, hard state and soft state. It was the first microquasar being detected in HE gamma-rays , via the satellites AGILE [4] and Fermi [5]. From the moment, no evidence of very high energy in gamma-ray emission has been reported.

II. GAMMA-RAY EMISSION

The study of gamma-ray emission provides a way to understand not only the processes of jet launching and accretion but also how cosmic rays are accelerated by non thermal processes. The high energy gamma-ray spectrum can be described as a power-law distribution with an exponential cutoff around a GeV.

There are two possible scenarios considered for the production of gamma-rays in binary systems. The microquasar scenario is based on VHE electrons accelerated in the relativistic jets interacting with photons from the companion star by inverse Compton (IC) scattering or synchrotron photons (SSC). This process consists in the scattering of photons with low energies to higher energies by relativistic electrons that will lose their energy. Strong and high density magnetic fields will give favorable conditions for the production of gamma-rays. On the other hand, in the pulsar scenario the relativistic wind of the rotating pulsar interacts with the stellar wind and/or Be disc of the companion. An alternative could be that protons in the stellar wind interact with relativistic protons from the jets, if their density is high enough, producing neutral pions which would decay into photons [6]. The intensity of the absorption, caused by the pair production cross-section and energy threshold, depend on the location where the gamma-rays origin, the observer and the companion star.

Pulsations would be a confirmation of a pulsar scenario. Contrarily, finding a mass of the compact object higher than 3 solar masses would imply a black hole, hence the microquasar scenario.

In a leptonic scenario, after the IC upscattering, the jet electrons would cool and they would become transparent to their radio syncrothron emission. Therefore, the gamma-ray flare is followed by a radio flare, but the lag between these two phenomenas varies from event to event. In an hadronic scenario, secondary processes would lead to a similar leptonic population and the same process would be observed [7].

In 2010, Cyg X-3 was confirmed to emit in high energy gamma-rays when it was detected with both AGILE and Fermi LAT [7]. It was reported that Cyg X-3 has a 4.8 hour gamma-ray orbital modulation [5]. Gamma-ray emission region cannot be too close to the accretion disk because it would be absorbed by pair production on the soft X-ray photons. The relativistic electrons from the jet scatter the ultraviolet photons from the star to gamma-rays via Inverse Compton. The modulation occurs because the radiation field of the star is anisotropic for the electrons and therefore, for the upscattered emission. When the jet points toward Earth and its electrons suffer a head-on collision with the UV photons is when the maximum gamma-ray emission is detected. Studying HE gamma-ray emission from Cyg X-3 provides a path to understand how non-thermal processes connect accretion power and relativistic jets.

Comparing the emissions in gamma-rays, radio and X-rays is found a correlation between them. Soft X-rays arise from the accretion disc, the radio from the jet and the hard X-rays from the corona [4]. Gamma-rays active periods occur close to radio flares. Based on previous detections, it is claimed that three conditions are required to detect HE gamma-ray emission: high level of soft X-ray emission (the 3–5 KeV RXTE/ASM value above 3 counts/s, soft state of Cyg-X3), low level of hard X-ray emission (Swift/BAT below 0.02 counts $\cdot$ $s^{-1}\cdot$ cm^{-2}) and the presence of significant emission with rapid variation from active relativistic jets (with 15-GHz radio flux above 0.2–0.4 Jy) [1]. Nevertheless, the relative timings between the different wavelengths are not clear yet: superposed multiple flares and particle acceleration and cooling could induce peaks and delays in the emission.

III. ANALYSIS FERMI LAT DATA CYG X-3

NASA's Fermi satellite was launched in June 2008 and it maps the entire sky every three hours. It includes an imaging gamma-ray telescope, Large Area Telescope (LAT), and the Gamma-ray Burst Monitor (GBM). LAT detects the photons through electron positron pair production. It covers an energy range from 20 MeV to 300 GeV. Cosmic rays have a larger flux than gamma-rays flux. Hence, it is necessary to differentiate between them; LAT rejects the other particles in the anticoincidence detector with a 99.97 % efficiency [8]. Its particle tracking detectors determine the incident photon directions through the reconstruction of the trajectories of the resulting electron-positron pairs. Then, the energies of the photons are measured in the calorimeter, where an electromagnetic shower develops. Data from Fermi LAT is of public domain and it is updated everyday.

To study Cygnus X-3 gamma-ray emission we had used the data from Fermi LAT which can be downloaded from the LAT data server. There are two LAT data filetypes: "event files", containing the information of events from the source (photons, their energy, time, coordinates…) and a "spacecraftfile", containing LAT location and information that is needed for the analysis [8].

In order to perform the analysis of the LAT data, two methods can be implemented: aperture photometry and likelihood. The latter is dependent of the background models in the source region of interest (ROI) while the aperture photometry analysis is done without considering them. The two methods are complementary. The common procedure is to first perform an aperture photometry analysis with the photon data in a small region of interest (typically 1°) around our source to inspect possible gamma emissions and once we have detected them, implement an extent likelihood analysis to confirm the results.

In the likelihood analysis we differentiate between Unbinned and Binned method. Unbinned is used for small data sets, where we inspect small number events of each bin, while in Binned analysis we are treating with high-density data.

We previously analysed the same data as The Fermi LAT Collaboration did in 2009 [5]. They inspected Fermi LAT data between 2008-2009 from Cyg X-3. In the article they found two main active periods: from 11 October to 20 December 2008 and from 8 June to 2 August 2009. It is in this same publication, where the orbital modulation of a 4.8 hour period from gamma-ray emission was reported for the first time. Afterwards, we implemented the same analysis to data between September 2018 to November 2019 in order to find other possible gamma-ray emission active periods.

To perform the analysis we have used the Science Tools (Fermitools) v11r5p3, released on February 15, 2018 [8]. As instrument response functions, we applied the latest "Pass 8 v2Diffusive".

The position of Cygnus X-3 is RA (J2000)=40.96°

and dec(J2000)=308.05° with a statistical uncertainty of 0.04° (95% confidence level) [5].

We obtained the LAT light curves implementing the aperture photometry. Using gtselect, photons were selected in an energy range from 100 MeV to 300 GeV. We also set a maximum zenith angle of 90 deg and an aperture radius of 1°. In the method it is required to select a small angle of aperture because we are not considering the background and this will focus into the events most likely originated in our region of interest. The gtmktime tool is used to select good time intervals, i.e it excludes times when the source is within 5 degrees of the Sun. To create our light curve, we selected linear binning with a bin width of one week using gtbin. Finally, using gtexposure, assuming a power-law spectrum of 2.7, we calculated the exposures for each time bin. Having done this, we obtained the light curves with the error bars. The next step was to estimate photon probabilities using gtsrcprob to find which events were likely to be from Cyg X-3. To do this, we previously performed an Unbinned maximum-likelihood within a source region of ROI+5deg. In the likelihood analysis we considered a background model containing the nearby pulsars PSR J2021+4026, PSR J2021+3651 and PSR J2021+4127 and the Galactic diffusive emission model gll_iem_v07.fit provided in the Fermi webpage [8]. The pulsars were modeled with an exponentially cut-off power-law model with all parameters set free to vary.

IV. RESULTS

A. 2008-2009

We studied the same period of data between 2008 and 2009 of the article published by Fermi LAT collaboration in 2009. They found two main active periods of high energy gamma-ray activity, from October to December, 2008 and from June to August 2009 (see Fig.1). We performed the aperture photometry method for different time binning. In figure 2, the lightcurves are shown for one week bins and the two periods of main activity can be observed with fluxes higher than $4 \cdot 10^{-6}$ photons $\cdot$ s$^{-1}\cdot$ cm^{-2} in agreement with the article [5].

Then, we performed two Unbinned likelihood analysis in order to compare results between a low and a high period of activity. Hence, the time intervals were selected in a high activity region, from June 7, 2009 (MJD 54489) to August 3, 2009 (MJD 55046), and in a low activity region, from December 30, 2008 (MJD 54830) to 10 March 2009 (MJD 54900).

In the active period, we obtained a flux of $(6.2 \pm 1.7) \cdot 10^{-7}$ photons $\cdot$ s$^{-1}\cdot$ cm^{-2} , a TS=64 (8σ), and a spectral index of -2.7 ± 0.1. In the energy range studied, it is predicted that 17 % of the photons observed come from the source. Furthermore, in the lightcurve represented for this period of time, 30 events are found to have a probability higher than 50 % of being from Cyg X-3. In the low period, we obtained a flux of $(5 \pm 26) \cdot 10^{-11}$ photons $\cdot$ s$^{-1}\cdot$ cm^{-2} . In the energy range studied, it is predicted that none of the photons observed come from the source. Hence, none of the events represented in the lightcurve in this low activity region are probable to come from it.

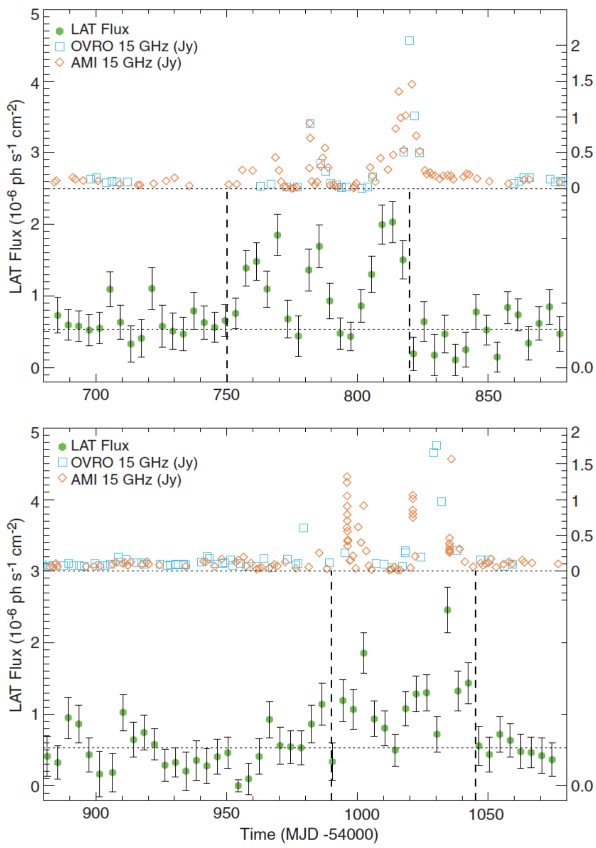

FIG. 1: Gamma-ray lightcurve of Cynus X-3 obtained by Fermi LAT Collaboration in 2009 with a likelihood analysis window of 4 days of Cyg X-3. The vertical dashed lines illustrate the active periods discussed. The bottom horizontal dotted line in each panel indicates the average gamma-ray flux at the location of Cyg X-3 outside the active periods. In addition, at the top of each panel, it is shown the Cyg X-3 15 GHz radio flux (from the AMI and OVRO 40-m radio telescopes). A horizontal dotted line at 0 Jy is also plotted for reference [5].

In the article that we have followed, [5], it is performed an extensive likelihood analysis of 4 days time scales in a ROI region of 15°. It is obtained an average flux of $(1.19 \pm 0.06){\cdot}10^{-6}$ photons $\cdot$ s$^{-1}\cdot$ cm^{-2} , and the results are compared with the radio data from the AMI telescope and the OVRO 40-m telescope at 15 GHz (see Fig.1). Radio flares are close to the gamma-ray active periods. It is reported a positive correlation between these two emissions, and a delay of 5 ± 7 days between the radio and the gamma-rays curves. This lag is interpreted as the propagation time of the relativistic ejecta, because radio flares are believed to occur farther out in the jet. Around December 10, 2008 (MJD 54810), it is detected the most intensive flare in radio and gamma wavelegths. It is also concluded that all gamma-ray active periods happen during the soft X-ray state of the source, having X-ray and gamma-ray the same asymmetric shape, with a slow rise followed by a faster decay.

The average flux observed in the light curve done by aperture photometry in figure 2 is $3{\cdot}10^{-6}$ photons $\cdot$ s$^{-1}\cdot$ cm^{-2} . This flux is higher than the one obtained by the article. This is coherent with the fact that in our method we are not considering the background. On the other hand, the flux that we obtained with the Unbinned likelihood analysis is lower. This could be due to the fact that we are using a different time binning and a smaller region of interest.

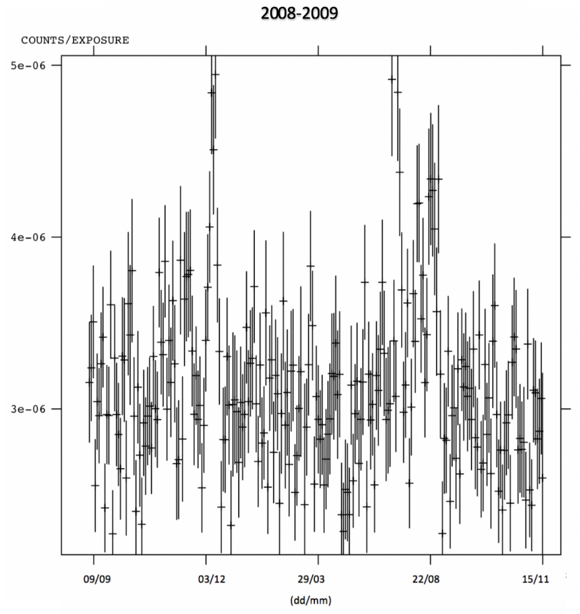

FIG. 2: Lightcurve at gamma-ray 2008-2009 done with an aperture photometry analysis of Cyg X-3 in one week bins. Fermi LAT data is used in a region of interest of 1° around the source. Error bars are also shown.

B. 2018-2019

The next step was to inspect more recent data in order to find other active periods in Cyg X-3. Since its launch, five main active periods in gamma-rays emission have been reported from Fermi LAT telescope: 2008 (October-December), 2009 (June-July), 2010 (May), 2011 (March) and 2016 (August) [2]. We selected recent data from September 2018 to November 2019. We followed the same criteria as in the aperture photometry analysis done between 2008-2009. We obtained a lightcurve using bins of one week and we observed a region of possible HE gamma-ray emission from March 23, 2009 (MJD 58565) to July 16, 2019 (MJD 58680) . Hence, we performed an Unbinned likelihood analysis in this time interval. We obtained a flux of $(4.2 \pm 0.7) \cdot 10^{-7}$photons $\cdot$ s$^{-1}\cdot$ cm^{-2} , a TS=81 (9σ) and a spectral index of $-2.7{\pm}0.1$. It is found that in the energy range studied, 13 % of the observed photons come from the microquasar. In the lightcurve obtained, 29 events are found to have a probability higher than 50 % of being from Cyg X-3.

Moreover, we applied the Unbinned likelihood analysis in a region of low activity: from December 30, 2018 to February 4, 2019. We obtained a flux of $(2.5 \pm 0.1) \cdot 10^{-11}$ photons $\cdot$ s$^{-1}\cdot$ cm^{-2} and none of the events have a probability of being from our source.

In conclusion, comparing with the results obtained for the data in 2008-2009, we report a region of high activity and a region of low activity in the period of time inspected (see Fig.3).

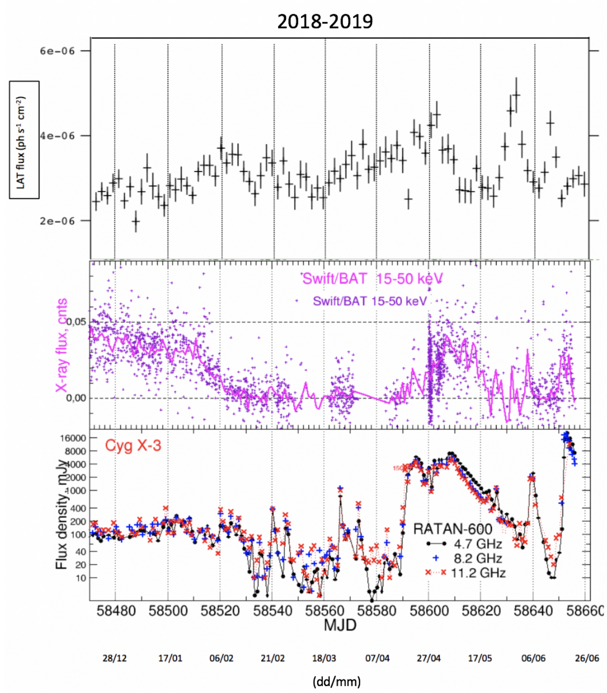

FIG. 3: Gamma-ray lightcurve of Cynus X-3 obtained in 2019. (Top) Lightcurve at gamma-ray done with an aperture photometry analysis in one week bins. Fermi LAT data is used in a region of interest of 1° around the source. Error bars are also shown. (Bottom) Light curves at X-ray 15-50 KeV and the multi-frequency radio data of the RATAN-600 measurements [11].

For the moment, there are no articles published about high energy gamma-ray emission from Cyg X-3 in this period of time. Therefore, we looked up for recent publications in the Astronomers Telegram (ATel). On April 22, 2019 a detection of gamma-ray flaring activity above 100 MeV from Cygnus X-3 was reported by AGILE, the gamma-ray astronomical satellite of the Italian Space Agency (ASI). Later, on June 27, 2019 it was also reported by AGILE that Cygnus X-3 was undergoing a prolonged gamma-ray activity [9]. It was observed a radio flux enhanced with doubled peaks on April 23 (6.55±0.72 Jy) and on May 5 (7.94 ± 0.03 Jy), 2019. Moreover, after 25 days of a quiescent state, it was observed again a new radio flare on June 18 [10].

From figure 3 it can be concluded that gamma-ray, X-ray and radio flux are correlated. The major radio and X-ray activity appeared to be approximately from April to June, which is in agreement with what has been reported. It is in this same period of time where we have reported the high activity period in gamma-ray activity. Furthermore, we observe a delay of gamma-ray peaks in comparison with radio and X-ray peaks. These results would be in agreement with the article published by Fermi LAT collaboration and they would confirm that during this period high activity was detected in all wavelengths.

V. CONCLUSIONS

We performed aperture photometry and Unbinned likelihood analysis for the Fermi LAT data in two different periods of time. We detected the two main periods of high activity in high energy gamma-ray emission expected between 2008 and 2009, following the study done by The Fermi LAT collaboration [3]. Then, we inspected the data from September 2018 to March 2019 by applying the same criteria. We found a epoch from March to July where there is a large probability of gamma-ray emission arriving from the source. We also found publications in ATel showing activity in Cygnus X-3 at other wavelengths in the same period of time. It is reported a correlation between them. We confirm that it was a period when Cygnus X-3 was emitting actively. The next step would be an exhaustive analysis of this region in this period of time. This would require a Binned likelihood analysis to study a larger region of interest and to apply different time bins. Cygnus X-3 appears to be a powerful source of cosmic rays particles and gamma-ray emission. More detections by Fermi LAT in high energy gamma-ray emission are expected in the following years.

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