Gamma-ray periodic emission in the binary system LS 5039

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Abstract: In the last two decades, astrophysicists have discovered one of the most important phenomena in the outer space: the existence of gamma-ray binary systems. Unlike the other binaries, these ones emit photons in high energy or very high energy. These are composed of a compact object and a massive star, which interaction causes the gamma-ray flux emission, that is known to be modulated by the orbital period of the system. Here, this orbital period is going to be our aim of study. Using data obtained by H.E.S.S. (High Energy Stereoscopic System), we are going to determine a periodicity that is coincident with the orbital period of the gamma-ray binary system LS 5039 using the Phase Dispersion Minimization (PDM) technique. With a programming language, we are going to implement a code to perform PDM with a trial of periods to, finally, get the real one.

I. INTRODUCTION

As researchers seek ways to improve existing technologies, astronomers take advantage of this fact to obtain instruments with high sensitivity and high angular and energy resolution, to better describe everything that surrounds us while finding solutions to the enigmas of the Universe.

One of the discoveries have been binary systems emitting high energy (HE, 0.1-100GeV) or very high energy (VHE>100GeV) gamma rays, which are called the gamma-ray binaries (Dubus 2013). These are composed of a compact object (black hole or neutron star) and a companion, that can be a high-mass ($\geq 10M\odot$) star or a low-mass ($\leq 1M\odot$) star.

These galactic binaries are bright in gamma-rays yet easily overlooked at other wavelengths. What makes them so bright in gamma-rays, is the fact that their non-thermal emission is due to particles accelerated at the shock between the wind of a massive star and the wind of a pulsar. Hence, gamma-ray emission is ultimately powered by the spin-down of a rotating neutron star with a strong magnetic field $\sim 10^{11} - 10^{13}$ G (Dubus 2013).

Two distinguishing features of gamma-ray binary can be mentioned. Firstly, there is a non-thermal emission with a peak above 1 MeV dominating its spectral energy distribution (SED), which goes from radio to gamma-rays. Secondly, they all have variable gamma-ray emission, sometimes modulated on the orbital period. Also, the spectral and brightness properties appear to be synchronised with the orbit of the binary system, which suggests that the physical conditions are periodic and reproducible.

The number of known VHE gamma-ray binaries is very limited. At the present, there are five binary systems classified, all of them with a young massive star as a companion. In 2004, the first binary called PSR B1250-63 was detected (Aharonian et al. 2005a). The second one was LS 5039 in 2005 (Aharonian et al. 2005b), followed by LS I +61°303 in 2006 (Albert et al. 2006). Then, HESS J0632+057 was found as a point-like source in the H.E.S.S. study of the Galactic Plane (Aharonian et al. 2007) and, finally, 1FGL J1018.6-5856 was found in a search for periodic flux variations from Fermi/LAT sources.

The origin of the VHE emission is still under debate. There are two excluding scenarios trying to explain it: acceleration in the jet of microquasar powered by accretion (microquasar scenario), or shocks between the relativistic wind of a young non-accreting pulsar and the wind of

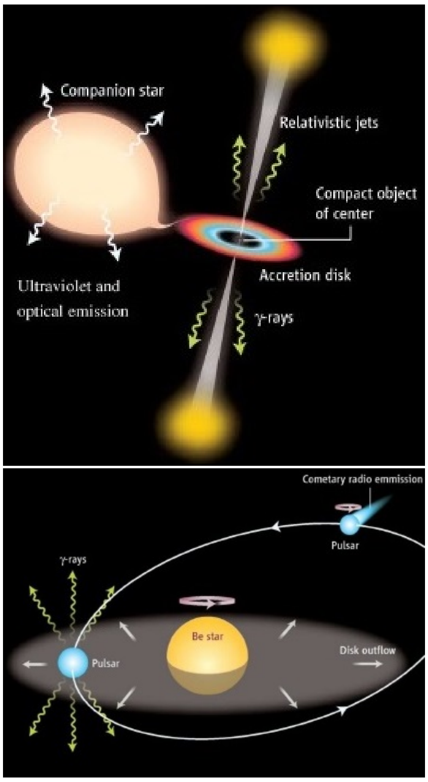

FIG. 1: Alternative scenarios for very energetic gamma-ray binaries: microquasar (top) and binary pulsar (bottom). From Mirabel (2006).

the stellar companion (pulsar scenario). Currently, the last one is the prevailing idea.

The microquasar-jet model (Fig.1(top)) was proposed after a study of VHE emission from LS 5039 (F. Aharonian et al. 2005b). In this scenario, microquasars are powered by compact objects via mass accretion from a companion star. This produces bipolar jets of relativistic plasma that, if aligned with our line of sight, appears as microblazars. When the jet particles collide with stellar UV photons, an emission of VHE gamma-rays is produced by inverse Compton scattering.

In the other hand, the pulsar scenario (Fig.1(bottom)) provides an explanation taking account that relativistic particles can be injected in the surrounding medium by the wind from a young pulsar. A young slow-rotating pulsar provides energy to the non-thermal relativistic particles in the shocked pulsar wind material outflowing from the binary companion. The gamma-ray emission is produced by inverse Compton scattering of the relativistic particles from the pulsar wind on stellar photons.

II. GAMMA-RAY BINARY SYSTEM LS 5039

LS 5039 is a gamma-ray binary system harbouring a compact object and a massive star that emits HE and VHE gamma rays. It is located at a distance of about ∼3.5 kpc from the Earth, only visible from the Southern Milky Way (l/b=16.88°/-1.29°), in the constellation of Scutum. The binary system was discovered by Motch et al. in 1997, cross-correlating X-ray sources from the ROSAT catalogue with OB star catalogues, in order to locate systems made of a compact X-ray source orbiting a massive star. They suggested that LS 5039 was a high-mass X-ray binary system. The detection of the binary by H.E.S.S. at energies above 250 GeV (Aharonian et al. 2005) proved that LS 5039 is even a gamma-ray source.

It is composed of a luminous O6.5V star and an unknown compact object orbiting around with a periodicity of $P_{orb} = 3.90603 \pm 0.001$ days (Casares et al. 2005). The nature of the compact object, either a black hole or a neutron star, remains unclear. A recent study, based on atmosphere model fitting to its spectrum, estimated its mass of about $M_x \sim 3.7 M\odot$ (Casares et al. 2005), which would point to a black hole rather than a neutron star. The compact object has a moderate eccentricity ($e \sim 0.35$) and an angle position in the plane of the sky barely constrained, $i \sim 20° - 60°$. The extremes values are adopted to define the compact object as a $1.4 M\odot$ neutron star if $i \sim 60°$, or as a $4.5 M\odot$ black hole if $i \sim 20°$. The companion star has $M = 23 M\odot$, $R = 9.3 R\odot$, $L = 2 \cdot 10^5 L\odot$ and T=39.000 K (Casares et al. 2005). The separation (centre-to-centre) between the two components varies between 2.2R at periastron ($\phi = 0.0$ with reference epoch T0 (HJD- 2 400 000.5) = 51 942.59) to 4.5R at apastron ($\phi = 0.5$), for a stellar radius $R = 7 \cdot 10^{11}$ cm. (See Fig.2)

LS 5039 is moving with more than 100km/s perpendicular to the Galactic plane, probably as a result of a recoil generated in the supernova explosion that generated the compact object (Ribo et al. 2002). It exhibits both flux and spectral modulation as a function of its orbital period. The X-ray and VHE gamma-ray fluxes display a maximum at inferior conjunction (when the compact object passes between the massive star and the observer) and a minimum at superior conjunction (when the compact object passes behind the massive star as seen by observer), with spectra becoming respectively harder or softer respectively, a behaviour that is completely reversed in the HE domain.

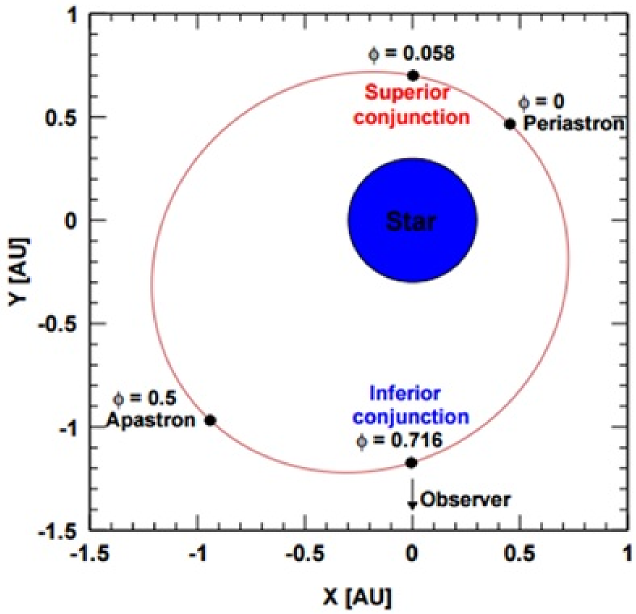

FIG. 2: The orbital geometry of the compact object around the O6.5V star. The arrow at the bottom indicates the direction to the observer. It is shown the periastron (ϕ_{per}=0), the apastron (ϕ_{ap}=0.5), the superior conjunction (ϕ_{sup}=0.058) and the inferior conjunction (ϕ_{inf}=0.716). The orbit is actually inclined at an angle in the range 13° $<i<$64 ° with respect to the view above. See Casares et al. (2005).

III. PERIOD DETERMINATION. PHASE DISPERSION MINIMIZATION

The phase dispersion minimization (PDM) technique was first developed by Stellingwerd in 1978. It is widely used for many types of data analyses in order to search for periodic components of a time series data set. It is useful for data sets with gaps, non-sinusoidal variations, poor time coverage or other problems that would make Fourier techniques unusable.

Taking into account a discrete set of observations, represented by vectors x (magnitudes) and t (observation times), the variance of x is given by:

$$\sigma^2 = \frac{\sum(x_i - \bar{x})^2}{N-1} \tag{1}$$

where N is the total amount of points, x_i is the i-th observed magnitude (i=1,N) and $\bar{x}$ is the mean $\bar{x} = \sum x_i/N$.

With the observation times vector t, a phase vector can be computed, using a trial period Π, as

$$\phi : \phi_\mathbf{i} = \frac{\mathbf{t_i - t_0}}{\mathbf{\Pi}} - [\frac{\mathbf{t_i - t_0}}{\mathbf{\Pi}}] \tag{2}$$

where brackets indicate the integer part.

The full phase interval [0,1] is going to be divided into a number N_b of compartments (bins), each of equal extent $1/N_b$. The input data are phased with a trial frequency and are distributed among the bins accordingly. Usually, a number of overlapping bins are considered, N_c, each cover offset in phase by $1/(N_bN_c)$ from the previous one, using periodic boundary conditions on the unit interval to obtain a uniform covering. Thus, M=N_bN_c is going to be the total amount of bins, each of length $1/N_b$, and whose midpoints are uniformly spaced along the unit interval at a distance of $1/(N_bN_c)$.

In Fig.3 is shown a typical bin structure, characterized by (N_b, N_c)=(5,2). Each of the input data falls into N_c bins.

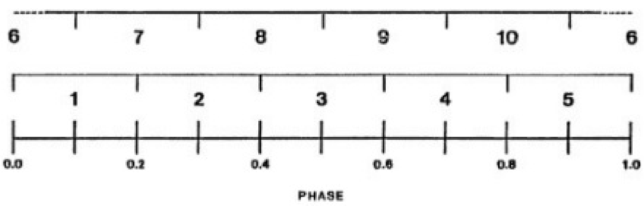

FIG. 3: Schematic of PDM (5,2) bin structure. Phase space is divided into N_b=5 equal bins, each extending for intervals of 0.2 in phase. There are N_c=2 set of covers; each set is offset from the other by 0.1 in phase. The total number of bins is M=10. Clearly each data point falls into 2 bins. See John R.Percy (1986).

For a particular trial frequency, the variances of the data assembled in each of the N_b,N_c bins are calculated and summed as

$$s^2 = \frac{\sum(n_j - 1)s_j^2}{\sum n_j - M} \tag{3}$$

where M is the total amount of distinct samples taken, s_j (j=1,M) is the variance of each sample according to equation (1), and n_j is the total amount of data point contained in it. The sum of the bin variances is compared with the global variance of the input data. We define the statistic

$$\Theta = \frac{s^2}{\sigma^2} \tag{4}$$

where s^2 is given by equation (3) and σ^2 is given by equation (1).

The ratio of the total bin variance to the global variance is going to be approximately unity ($\Theta \approx 1$) in most trial frequency. That is because a random distribution of data points in phase space is produced. Alternatively, the ratio Θ achieves a minimum when the trial frequency corresponds to the true period, with value hopefully near zero. Thus, the scatter within the phase bins is reduced. In a plot theta vs. frequency, the frequency of the true periodicity is indicated by a deep minimum.

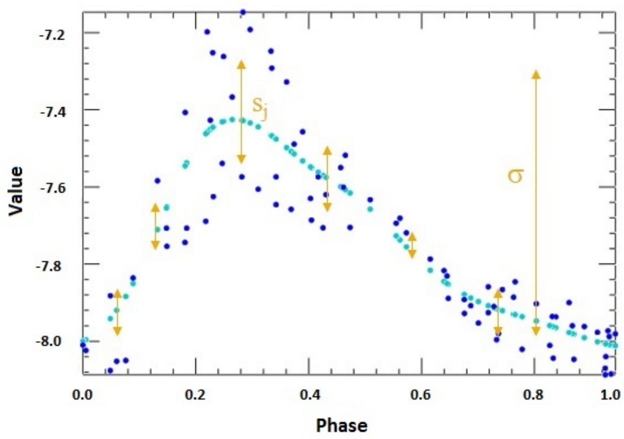

FIG. 4: Representations of the global variance Θ and the variance of each sample s_j. See Stellingwerf (2011).

IV. VHE OBSERVATIONS OF LS 5039 WITH H.E.S.S.

LS 5039 was first detected in VHE gamma-rays in 2004 (Aharonian et al. 2005b) with H.E.S.S., an array of four identical Atmospheric Cherenkov Telescopes (ACT) located in the Southern Hemisphere, and sensitive to gamma-rays above 0.1 TeV. The system was detected during an observation ($\sim 11h$) during the H.E.S.S. Galactic Plane survey (Aharonian et al. 2005b). Observations established that LS 5039, and hence X-ray binaries (XRBs) are capable of multi-TeV (10^{12} eV) particle acceleration.

In 2005, the 2004 H.E.S.S. observations were followed, concluding with a total dataset of 160 runs representing 69.2h observations from both years. To optimize the coverage over the orbit, the observations were spread over more than six months, resulting in a wide range of observations conditions. The observations are in a threshold varying between 100GeV and 1TeV.

These observations revealed that LS 5039 VHE gamma ray emission is modulated by the orbital motion of the compact object around its massive stellar companion.

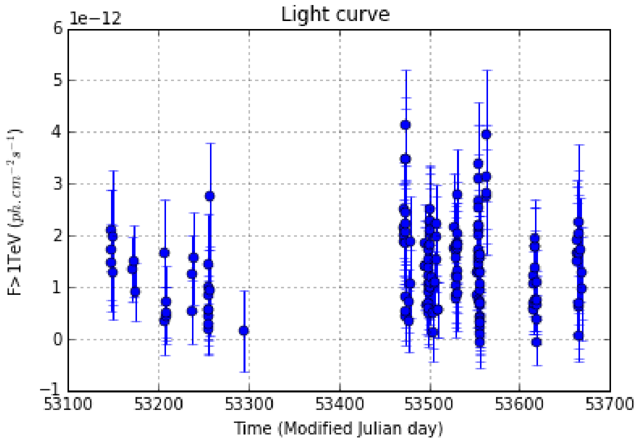

FIG. 5: VHE gamma-ray flux (E>1TeV) vs.time (MJD) for LS 5039. The discovery of the variability is made in one season. A few follow-up tests are being done some months later, confirming the variability, and a dedicated campaign is then undertaken to derive the periodicity in the next year.

V. ANALYSIS AND RESULTS

In this section, we are going to analyse the orbital period of the compact object resulting from using the PDM method explained above. We have written a Python code that computes the PDM method with data set obtained by H.E.S.S. from May 2004 to October 2005, with a gap between October 2004 to April 2005, as seen in Fig.5.

Our PDM method is characterized by (N_b, N_c)=(10,2), taking into account that every bin has a minimum number of points, being N=160 the total amount. We have defined trial periods between 0.5 and 20 days separated 0.01 days, so the program will run within a covered range of periods. Hence, a phase vector is determined by equation (2). For each trial, bins are distributed into the phase space according to boundary conditions and, then, variance s^2 is calculated and compared with the total data variance σ^2. We will obtain different values of Θ for each period trial.

In Fig.6, we represent Θ vs. period (days). We can see that a minimum is given for a period value of 3.905 days. Thus, this is in coincidence with the orbital period of the compact object around the massive star.

Taking this period value, we can obtain the phasogram (Fig.7) of integral fluxes at energies E>1TeV vs. orbital phase. We have calculated the orbital phase ϕ according to equation (2), taking t_0=51942.59, which is the reference epoch of ϕ=0.0.

As seen in the phasogram, the behaviour of the VHE gamma-ray flux as a function of the orbital phase ϕ is approximately sinusoidal. The emission shows a bulk confined between phase interval $\phi \sim 0.45$ to 0.90. There is a maximum near $\phi \sim 0.80$, aligning with inferior conjunction (ϕ=0.716), and a minimum at phase $\phi \sim$ 0.20, slightly further along than superior conjunction (ϕ=0.058) (Dubus et al. 2006a). Inferior conjunction (INFC) compresses orbital phases between $0.45 \leq \phi \leq 0.9$ and, superior conjunction (SUPC), between $\phi \leq 0.45$ and $\phi \geq 0.9$. We have neglected the phase error due to uncertainties in the period measurement ΔP=0.00017 days since it is very small, $\Delta\phi = 0.01$ (Casares et al. 2005).

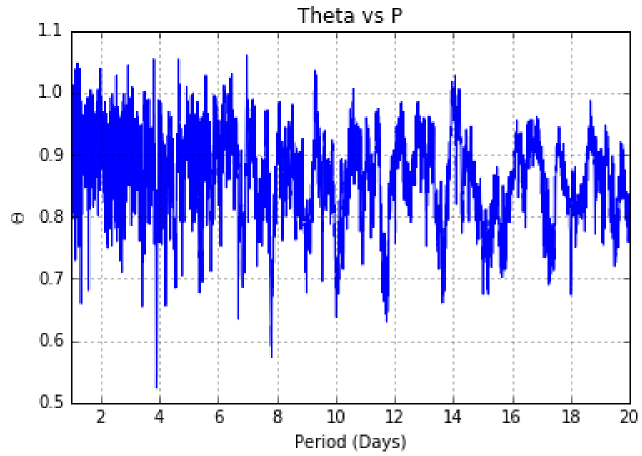

FIG. 6: Θ representation as a function of the period (days), obtained using PDM method. The minimum value of Θ corresponds to a period value of P=3.905 days.

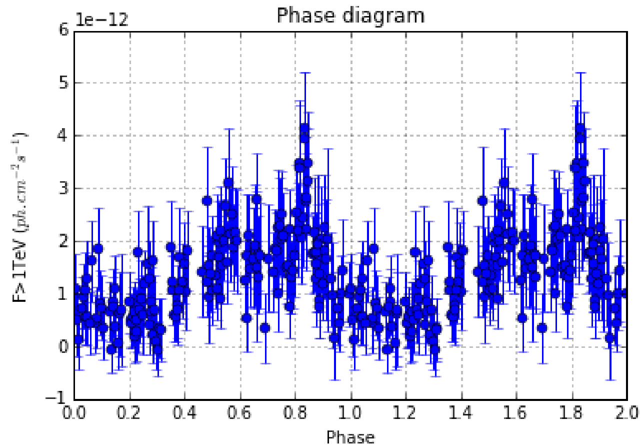

FIG. 7: Gamma-ray flux as a function of the orbital phase (phasogram) of binary system LS 5039. A maximum is seen in $\phi \sim 0.80$, near INFC, and a minimum in $\phi \sim 0.20$, near SUPC. Two periods are shown for clarity.

VI. DISCUSSION

Gamma-ray binaries are composed of two objects, a massive star and a compact object, which interaction causes gamma-ray emission. It is known that this emission is modulated by the orbital period, which has been our aim of study.

Here, we have studied LS 5039 gamma-ray binary system, a system with VHE gamma-ray emission. With data taken by H.E.S.S. between 2004 and 2005, containing a total amount of 160 points, we have written a Python code that computes the Phase Dispersion Minimization (PDM) method to determinate the period of the compact object around the massive star.

Our results clearly show the existence of the orbital modulation. It is seen in the phasogram (Fig.7), where VHE flux is represented as a function of orbital phase ϕ. This phasogram shows a peak flux around inferior conjunction, which occurs when the compact object is lined up along our line-of-sight in front of the stellar companion, and a minimum flux around superior conjunction, which occurs when the compact object is lined up behind the stellar companion

In Fig.6, we represent Θ vs period (days). We can see that a minimum is given for a period value of 3.9050 ± 0.001 days. Thus, this is the true period determined by PDM method. According to Aharonian et al. (2006), where the period determination was carried out using Lomb-Scargle Test and Normalised Rayleigh Statistics (NRS), the period is 3.9078 ± 0.0015 days. Casares et al. (2005), alternatively, determined a period value of 3.906 ± 0.001 days using optical spectroscopy. We can see that the obtained period value is consistent with both alternative techniques.

VII. CONCLUSION

It was discovered that the emission of gamma-ray binary systems is usually modulated by the orbital cycle of the system. This suggests that physical conditions within are periodic and reproducible, which make them interesting objects of study. In particular, VHE gamma-ray binary system LS 5039 has been observed by H.E.S.S. from 2004 to 2005, which confirmed the orbital modulation of the VHE gamma-ray flux. The period determined with the PDM method of 3.9050 ± 0.001 days, provides us the phasogram, giving an idea of the modulation of the flux as expected, indicating gamma-ray absorption within an astrophysical source. We can observe a peak flux ($\phi \sim 0.80$) around INFC, behind the apastron epoch, and a minimum ($\phi \sim 0.20$) in SUPC.

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[1] Aharonian, F., Akhperjanian, A. G., Aye, K.-M, et al. 2005a, A&A, 442, 1
[2] Aharonian, F., Akhperjanian, A. G., Aye, K.-M, et al. 2005b, Science, 309, 746
[3] Aharonian, F., Akhperjanian, A. G., Aye, K.-M, et al. 2006, A&A, 460, 743
[4] Albert, J., Aliu, E., Anderhub, H., et al. 2006, Science, 312, 1771
[5] Aharonian, F., Akhperjanian, A. G., Aye, K.-M, et al. 2007, A&A, 460, 743
[6] Casares, J., Ribó, M., et al. 2005, MNRAS, 364, 899
[7] Dubus, G. 2006a, A&A, 451, 9
[8] Dubus, G. 2013, A&A Rv, 21, 64
[9] Mirabel, F. 2006, Astrophysics and space science
[10] Motch, C., Haberl, F., Dennerl, et al. 1997, A&A, 323, 853
[11] Percy, J.R. (Ed.): *The study of variable stars small telescopes.* 1ª ed. Cambridge University Press, 1986
[12] Ribó, M., Paredes, J.M., Romero, G.E, Bengalia, P., et al. 2002, A&A v.384 954, 964
[13] Stellingwerf, R.F.: *Detecting periodicities in RR Lyrae Stars.* Power Point presentation. Pasadena, California. 24 January 2011