# Quasi-periodic modulation observed in the gamma-ray blazar PG 1553+113 and the MAGIC campaign 2015-2017

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**Abstract.** A gamma-ray nearly-periodic oscillation was observed from the well-known GeV/TeV BL Lac object PG 1553+113 by the Fermi Large Area Telescope (LAT). The quasi-periodicity in the gamma-ray flux (E>100 MeV and E>1 GeV), reported for the first time in an active galactic nucleus, is significant with a < 1% probability over red-noise fluctuations. The period of the gamma-ray modulation is 2.18 ± 0.08 observed with 3.5 oscillation maxima. It is supported by significant cross-correlated variations observed in radio and optical flux light curves. Interestingly, one of the physical scenarios that can account for such variability pattern is the presence of a supermassive black hole binary in the nucleus of PG 1553+113. The MAGIC telescopes have observed PG 1553+113 at VHE since 2005. An intense multi-wavelength (MWL) campaign started in 2015 aimed at revealing the physical scenarios that can account for such a variability pattern. The campaign will regularly monitor the source activity from radio to VHE (E>100 GeV) gamma rays and will cover the next maximum of activity, expected between the end of 2016 and beginning of 2017. The MWL data collected during this campaign, coupled with the gamma-ray ones form MAGIC, will be the key to determine the nature of the periodicity to disentangle the processes driving the periodic modulation from flaring activity typical in blazar objects.

## INTRODUCTION

Active galactic nuclei (AGN) are powered by the gravitational energy extracted by the matter in the accretion disk bound to a compact central object, presumably a supermassive black hole (SMBH) of $10^6$ up to $10^{10}$ $M_\odot$. In radio-loud AGN a pair of jets is formed from the relativistic outflow expelled by the central SMBH. Variability on a wide range of time scales is a common trait of AGN at all frequencies. AGN variability is linked up to the emitting region and to the processes responsible for the emission, hence providing essential information of the central sub-pc regions of the AGN. In fact, a coherent description of the physical processes acting in the AGN must match the observed light curves and variability time scales of the continuum, and the correlations and delays between different wavelengths.

Among AGN the blazars subclass is dominated by the emission from relativistic outflow emerging from the SMBH and structured in beamed jets, namely forming a small angle with the observer. The relativistic beaming amplifies the observed radiation and results in a broad spectral energy distribution (SED) dominated by the continuum, showing two main humps. The first peaks in the IR to X-ray region, presumably originated by synchrotron radiation, and the second hump spans from the UV up to the TeV. Blazars are distinguishable for the extreme variability of their flux, with the largest amplitude – up to two orders of magnitude– and extremely fast variations, down to few minutes. As a consequence blazar variability points directly to the physical processes occurring in the jet or feeding it. The emission models of jets can be tested looking at the variability pattern and correlations between the low energy and high energy hump of the SED [1], built through contemporaneous multi-wavelength (MWL) monitoring campaigns [2]. In this framework the discovery of regular and periodic patterns, in the otherwise apparently stochastic variability,

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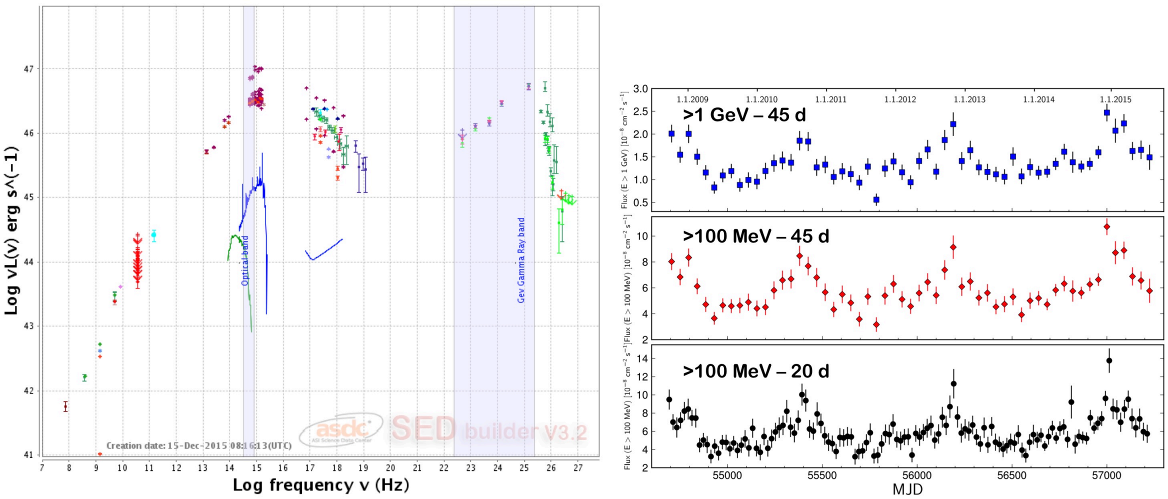


**FIGURE 1.** Left: PG 1553+113 SED. The templates of an elliptical galaxy, typical host of blazars, and of a accretion disk at $z \sim 0.5$ is shown for comparison to the overwhelming continuum emission. From ASDC tools `http://www.asdc.asi.it`. Right: PG 1553+113 light curves above 100 MeV with 20 and 45 days binning and above 1 GeV measured with *Fermi* LAT . From [11].

are essential to the understanding of the physical processes, since they directly point to the central source, or to the intrinsic properties of the emission mechanism.

One of the longest historical light curve of a AGN is the one collected on the blazar OJ 287 [3]. Its length, $\sim$ 100 years, should be compared to the lifetime and the duty cycle of the AGN activity, typically assumed as $10^7 - 10^8$ years, or to the episodic nuclear activity and jet formation $\sim 10^5$ years [4, 5]. Any claim of periodicity must take this aspect into consideration, establishing a compelling statistical evidence emerging from the stochastic fluctuations that can mimic a periodic pattern. Among blazars a handful of objects show a possible periodic variability, usually on very few cycles [6, 7, 8]; none of these have been shown a consistent period in gamma rays and in the other wavelength. Beside the observational evidence, a sound description of the underlying periodic processes is mandatory in providing a self consistent physical interpretation which in turn must be supported by observations.

The large area telescope (LAT) on-board the *Fermi* satellite is an ideal instrument to detect AGN periodicities, thanks to the continuous all-sky survey at energies above 100 MeV. After 8 years of operation *Fermi* LAT has provided few hints of periodic modulation in the light-curves of the blazars 1ES 2155-304 and PKS 0537-441 [9, 10] and a detection of a $\sim$ 2 years quasi-periodic variability on the blazar PG 1553+113, confirmed in the optical lightcurve [11].

In this work we will focus on the latter, with a short description of the periodic emission and its possible interpretation (sect.a)), of the observation efforts arranged by the MAGIC collaboration to provide a detailed and regular MWL coverage (sect.a) aimed at confirming the periodicity in the VHE and X-ray bands and at giving a comprehensive multifrequency description of different phases to constrain the interpretation (sect.a)).

## PERIODIC MODULATION OF THE BLAZAR PG 1553+113

PG 1553+113 is one of the brightest high frequency peaked BL Lac (HBL) emitting at gamma-ray energies, located presumably at $0.4 < z < 0.67$ [12, 13]. It is also a strong X-ray emitter, and thus a ideal probe for the detection and measurement of the warm intergalactic medium [14]. Its comparably large redshift entails a strong attenuation of the gamma-ray flux above energies E > 250 GeV due to pair production with photons of the extragalactic background light (EBL). Albeit this attenuation, PG 1553+113 is a well known TeV gamma-ray emitter observed by all major imaging air Cherenkov Telescopes (IACTs): H.E.S.S., MAGIC, and VERITAS [12, 15, 16]. As other gamma-ray emitters belonging to the class of blazars, the energetic non thermal emission originates in a relativistic jet and has a SED characterised by two humps overwhelming any other component from the nucleus or the host galaxy (fig.1).

The continuous gamma-ray lightcurve collected by *Fermi* LAT since 2008 shows a clear signature of a periodic modulation of 2.18 ± 0.08 years at E> 100 MeV and E> 1 GeV, covering 3.5 cycles [11]. The periodicity has < 1%

chance of being red-noise random variability. Optical fluxes correlate with the gamma-ray emission at 99% confidence and the optical light curve shows evidence for modulation of 2.06 ± 0.05 years over 4.5 cycles.

Such a modulation might point to interesting physical phenomena, including precession of the jet, an intrinsically rotating flow, quasi-periodicity in the mechanism feeding the jet, such as pulsational accretion flow instabilities, or the tantalizing possibility of a binary super massive black hole system (see the discussion in [11]). Each interpretation leads to different expectations: in particular, interaction between the two black holes of a binary system would produce multiple-peak signatures [17, 18] and such a complex structure can be already glimpsed in the available light-curves. A better characterization of these substructures, especially in the gamma-rays and X-rays, is strongly needed to clarify the picture. Unfortunately the *Fermi* LAT sensitivity on blazars with hard spectra as PG 1553+113, requires a long integration time >~ 20 days to yield a significant flux measurement. This washes out the shorter substructures visible for example in the optical light curve. Instead Cherenkov telescopes like MAGIC, thanks to the large collection area and low energy threshold, can detect the source with integration time as short as one hour, also during the low phase.

Other viable scenario can be discriminated studying the interdependencies between different energy bands. They can shed light on the the acceleration mechanism in the jet, or point to a geometrical origin of the periodic modulation [19, 20], due to the variation of the beaming factor with the change of the viewing angle [21]. Hence almost achromatic variability is expected at all wavelengths, or with clear correlations among different wavelengths [22].

To this aim an extensive monitoring campaign was planned by the MAGIC collaboration, with a comprehensive MWL program started on late 2014, when the periodicity of PG 1553+113 was first suggested. This will not only clearly confirm or reject the claim of periodicity, but will assure, in case of confirmation, the most complete and wide possible spectral coverage of PG 1553+113 across the predicted maximum and will therefore provide the necessary diagnostics to discriminate between the very different, and all at the moment viable, explanations for the observed modulation.

## MAGIC and the MWL CAMPAIGN

MAGIC is a system of two IACTs located in La Palma, Canary Islands, at 2200 m asl. It observes VHE gamma rays from 50 GeV up to tens of TeV. The angular resolution at around 200 GeV energies is < 0.07 degrees, while the energy resolution is 16% [23].

Since its detection in 2004, MAGIC carried out several MWL observations of PG 1553+113. The results reported for the single-telescope observations and related to the years 2007, 2008, and 2009, were already published in [15]. In April 2012 PG 1553+113 underwent a remarkable flaring activity for few weeks, that provided interesting results on the emission and on the EBL absorption [24]. In 2013, planned high-energy observations by MAGIC in April, June and July triggered a multi-wavelength campaign by the WEBT Collaboration. The results were published in [25] and show an enigmatic synchrotron behaviour with a complex UV and X-ray SED. This has been interpreted with an helical jet model that, interestingly, can explain periodicities by assuming a rotation of the helix induced by the orbital motion of a binary black hole system [26]. To investigate the quasi-periodic modulation and to shed light on the underlying mechanism, we commenced a comprehensive multi-wavelength program including radio (OVRO), infrared (REM), optical (Tuorla/KVA), ultraviolet (*Swift*-UVOT ) and X-ray bands (*Swift*-XRT ). The data collected from 2009 to 2015 and the MWL data are under analysis and preliminary results are shown here.

*A multi-wavelength campaign covering 2016 and lead by the MAGIC Collaboration is currently ongoing aiming to follow the new high activity expected in 2017.* In fact, according to the two-years modulation, an increase of the flux in the optical and gamma-ray bands is expected at the beginning of 2017, possibly lasting few months. In May 2016 an outburst with a duration of few weeks was followed during the monitoring campaign [27], resembling the flare observed in 2012.

The forthcoming observations represent an unique opportunity to confirm the periodicity in the VHE band and in the UV and X-ray bands with the *Swift*-UVOT and XRT instruments. The regular and frequent monitoring will reveal the complex structure of the lightcurves and its interdependence between different bands.

## PRELIMINARY RESULTS

Figure 2 reports the light curves emitted by PG 1553+113 at several wavelenghts, from radio (top panel) to VHE gamma-rays (bottom panel), in the last 11 years. For data from radio to X-rays, the flux registered at each pointing is displayed as a separate bin. High-Energy (HE) gamma ray data collected by *Fermi*/LAT are analyzed with a 20 days

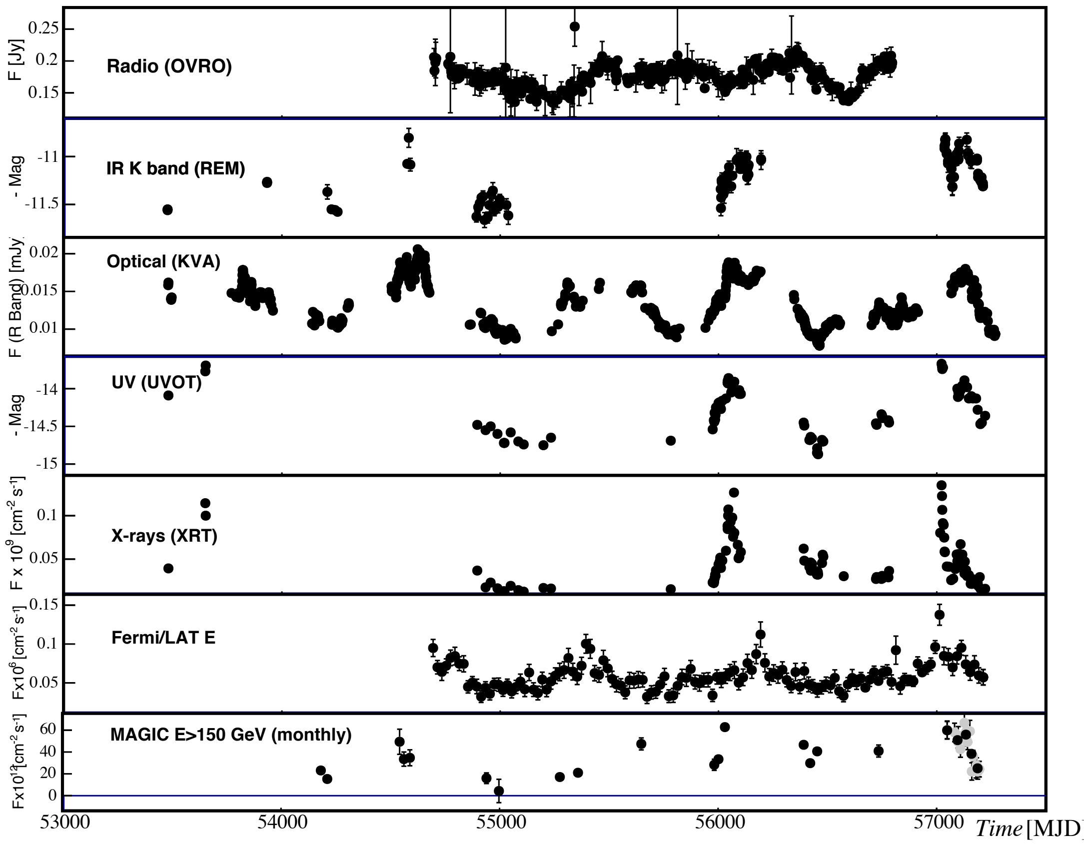


**FIGURE 2.** PG 1553+113 light curve above 150 GeV measured with the MAGIC telescopes. A monthly binning is adopted for data collected with a single telescope (MJD < 55000), while a daily binning is used otherwise.

binning. The *Fermi* LAT gamma-ray lightcurve and radio and optical datasets, are published in [11] and were used for the periodicity analysis.

The only instrument considered in this work that performed a continuous monitoring is *Fermi* LAT . Also radio data have a very good coverage, followed by optical data that suffered only from few months break per year related to the visibility of the source. The light curve is sparsely sampled for IR, UV, X-rays, and VHE gamma-ray data, in correspondence of flaring episodes and is thus biased towards high states. In these bands, the coverage had a clear improvement starting from late 2014, MJD ~57000. This is the result of an intense multi-wavelength and multi-year campaign aimed at a precise monitoring of the source state for the detailed modelling of the source emission.

From a visual inspection of Figure 2 we can conclude that the source shows a clear activity along the years in all the bands, with moderate variations in radio and more pronounced variations in X-rays and gamma rays. This behaviour is quite common in HBL. A periodic modulation of the HE gamma-ray emission is clearly visible in *Fermi* LAT data. The optical curve appears much more complex than *Fermi* LAT curve, but also in this case a modulation with period similar to that observed at higher frequencies is found, even if with a smaller significance. Part of the purpose of this work is that of searching in other frequencies an evidence for such modulation. The low statistics available to now and, even more important, the very sparse sampling affecting the datasets prevent us to extend to other bands the wavelet analysis and Lomb-Scargle test studies carried out in [11] for *Fermi* LAT and optical data. The MWL lightcurves is then folded with the period $P_{fermi}$ = 798 days to test if the light curves at different bands are in agreement with the hypothesis of such a periodic modulation. The multi-wavelength folded light curve displayed in Fig. 3 shows the averaged emission for two phases of period $P_{fermi}$, obtained for all the bands reported in Fig 2.

As expected, the HE gamma rays folded curve displays a clear peak at phase $\sim 0.1$. The minimum emission is instead located at phase 0.3–0.5. The same trend is observed in the optical folded curve (second panel) while the radio curve seems to suggest a delayed emission, confirming the findings reported in [11].

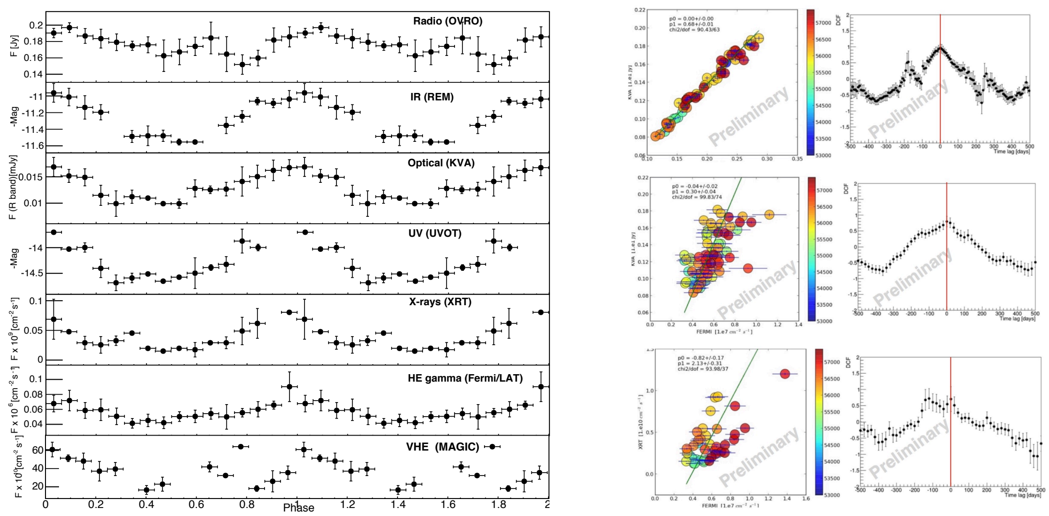


**FIGURE 3.** Left: PG 1553+113 multi-wavelength folded light curve. Right: Correlation and time lags between different energy bands. The colors corresponds to different observation MJD, as reported in the legend.

It is very interesting to note that despite the poor sampling of the light curves, the IR, UV, X-ray, and VHE gamma ray folded curves are almost fully characterized, meaning that the observations carried out in the last 11 years were diluited in different phases of the assumed periodic modulation. This allows us a first, qualitative study of the trend of these curves, that can be summarized as follows:

- an enhancement of the average emission is visible in all the light curves in correspondence to the phase interval 0.9–1.2, i.e. almost simultaneously with what observed in HE gamma-ray and optical curves;
- the folded curves shows a minimum in the phase interval 0.3-0.5, once again in agreement with the observations in the HE gamma-ray band;
- in addition to the trends in common with the optical and HE gamma-ray curves, there are some outliers, namely the peak at phase 0.7–0.8 in the UVOT and VHE gamma-ray curves and the small peak at phase 0.35 in the X-ray curve.

These findings obtained from a first analysis of the folded curve could pinpoint, if confirmed, to a common origin of the emitted ligtht for almost all the bands. An exception is represented by the radio emission, which is in any case a well known fact in blazar modeling and usually explained with a different emission region. Local deviations from the observed common behaviour for the other bands could be due to episodic events superimposed to the overall modulation and enhanced by the lack of statistics.

In order to better check a possible correlation between different bands and their statistical significance, a discrete correlation function test was done. This test gives also the opportunity to find time lag between the emission of two bands, in case of correlation. Preliminary results on few cross-correlation between X-ray, optical and gamma-ray band do not show any time lag (see fig.3). The correlation is rather linear. Although a more complex behavior between X-ray and high-energy gamma-rays is visible, in a first approximation the MWL variations look achromatic, pointing at a geometrical origin of the modulation, as expected from a variation of the beaming through a changing viewing angle. But a firm conclusion cannot be drawn yet. A deeper study on correlations will be addressed in a future work, as well as the comparison of SED evolution in different phases of the modulation.

## CONCLUSIONS

PG 1553+113 is the first gamma-ray blazar with a compelling evidence of quasi-periodic modulation in the correlated gamma-ray and optical light curves. The sampling in other wavelengths, despite their sporadic distribution, suggests that the quasi-periodic trend found in optical and gamma-rays is also present. The preliminary results shown here show that the flux variations in other bands correlates to the modulation seen by *Fermi* LAT , without any apparent time lag, with the exception of the 15 GHz radio lightcurve. The global multi-frequency trend, also visible in the lightcurves folded with the measured period, suggests a common origin for the modulated emission. Local deviation in the optical, X-ray and MAGIC folded curves can be a consequence of episodic events superimposed to the overall modulation, and of the bias of the unevenly sampled lightcurves in those bands. Future unbiased and regular observations will clarify this picture and will shed light on the mechanism driving the periodicity, if confirmed.

The observed periodicity can be interpreted as a periodic perturbation of the accretion rate on the SMBH and consequently of the fuelling at the base of the jet. The presence of a secondary black-hole in a sub-parsec orbit respect to the primary SMBH originating the jet represents a natural explanation [28], as previously invoked for OJ 287, despite not unique. Different mechanisms as jet precession, internal jet rotation, or helical jet motion may be invoked. The orbital scenario is corroborated by the indication of a double or multiple peaks structure in the optical light curve, as expected by the interaction of the secondary BH with the accretion disk near the periastron. The detection of a similar double-peaks structure in the gamma-ray light curve would confirm this interpretation. Unfortunately present data cannot neither confirm, nor reject the presence of this structure. A fine time coverage by the MAGIC Cherenkov telescopes in the $E > 100$ GeV band, which have higher sensitivity on these hard gamma-ray blazars, will allow to disentangle the light curve structure in VHE. An extensive multiwavelength campaign is ongoing aiming at observing PG 1553+113 during the next maximum of the modulation, expected at the beginning of 2017.

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