THE BLAZAR PG 1553+113 AS A BINARY SYSTEM OF SUPERMASSIVE BLACK HOLES

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ABSTRACT

The BL Lac PG 1553+113 has been continuously monitored in gamma rays with Fermi-LAT for over 9 years. Its updated light curve now includes 5 iterations of a main pattern comprising a high peak and a longer trough, with a period \( P \approx 2.2 \) yr. Our analysis of 2015-2017 data confirms the occurrence in January 2017 of a new peak fitting in the previous trend. In addition, we identify secondary peaks (“twin peaks”) that occur in closely symmetric pairs on both sides of most main peaks, including the last one; their occurrence is supported by correlated X-ray outbursts. We stress that the above features strongly point to binary dynamics in a system of two black holes (BHs) of some 106 and 107 \( M_\odot \). At periastron the smaller BH periodically stresses the jet \( j_1 \) launched by the heavier companion, and triggers MHD-kinetic tearing instabilities. These lead to magnetic reconnections and to acceleration of electrons that produce synchrotron emission from the optical to X-ray bands, and inverse Compton scattering into the GeV range. For the origin of the twin peaks we discuss two possibilities: a single-jet model, based on added instabilities induced in \( j_1 \) by the smaller companion BH on its inner orbital arc; and a two-jet model with the smaller BH supporting its own, precessing jet \( j_2 \) that contributes lower, specific GeV emissions. Such behaviors combining time stability with amplitude variations betray plasma instabilities driven in either jet by binary dynamics, and can provide a double signature of the long-sought supermassive BH binaries.

Subject headings: gamma rays: observations – BL Lac Objects; individual: PG 1553+113.

1. INTRODUCTION

The blazar PG 1553+113 is a BL Lac Object at a redshift \( z \approx 0.5 \), detected in the optical band and at X-ray, GeV and TeV energies. The first detailed study in the GeV range has been performed by \cite{Abdo:2010uu} and followed up by Fermi-LAT at GeV energies \cite{Ackermann:2015hja}, hereafter A15. In fact, Fermi-LAT was able to continuously monitor PG 1553+113 over a long stretch of time, from 2008 August 4 to 2015 July 19. This 6.9-year long data stretch reported in A15 showed a quasi-periodic trend, with main peaks of gamma-ray emission occurring over a period \( P \approx 2.18 \) yr (observer frame, corresponding to \( P/(1 + z) \approx 1.5 \) yr in the source frame) at a confidence level greater than 99\%. Optical monitoring of the source shows prolonged enhancements and emission minima in qualitative agreement with the gamma-ray overall trend (A15). Furthermore, sparse X-ray monitoring of the source indicates the existence of a more sporadic behavior of X-ray flaring not always correlated with the GeV main peaks.

The periodic GeV emission admits an interpretation in terms of a binary supermassive black hole (SMBH) system. Establishing with certainty the binary nature of a SMBH system such as PG 1553+113 would have very significant implications concerning study of blazar jets and BH evolution as advocated by e.g. \cite{Rieger:2007} and would indicate opportunities for future gravitational wave detections from SMBHs by projects such as the evolving LISA (cfr. \cite{Amaro:2017}).

In the present paper we take up the challenge, and report first our analysis of new publicly available gamma-ray and X-ray data starting from July, 2015 until September, 2017. This additional 2-year interval contributes considerable information on PG 1553+113. We therefore extend the analysis of A15 and confirm the periodic nature of the GeV emission by determining the existence of a 5th main peak in the gamma-ray light curve that we find in January 2017. The timing of this peak is in agreement with the epoch expected by A15 based on the period \( P \approx 2.18 \) yr. Furthermore, we identify the existence of secondary “twin peaks” of GeV and X-ray emissions that occur soon before and after the main GeV peaks. We present in Sect. 2 the results of our analyses of the updated data that support these findings.

We then turn to theoretical interpretations of these emission features. First we recall our context. BL Lac Objects such as PG 1553+113 constitute a subclass of blazars. These are marked among the quasars by narrow, relativistic jets of electron-proton plasma and embedded magnetic field with a substantial axial component. The jets are launched by a central supermassive black hole (SMBH) with mass \( M \sim 10^8 - 10^9 M_\odot \), and flow upward of its accretion disk with bulk Lorentz factors \( \Gamma \sim 10 \). Thus their radiations are boosted and collimated and appear so bright as to “blaze” the observer when aligned with the line of sight within angles \( \theta \approx 1/\Gamma \). On the other hand, many similar if inconspicuous objects (a number \( \Gamma^2 \) times larger) are expected to exist outside this angular range.

The observed outputs are variable and up to some
10^{17} \text{ erg/s} in non-thermal radiations produced by highly relativistic electrons with random Lorentz factors up to $\gamma_p \sim 10^7$ accelerated in the jet. In fact, BL Lacs lack - or hide in the central throat of their thick accretion disk - thermal features such as the broad optical lines and the Big Blue Bump shining in many quasars including the other blazar subclass, the Flat Spectrum Radio Sources.

In BL Lacs the spectral energy distribution (SED) is constituted by two nearly level humps: one – peaking in the $IR - UV$ and declining toward the soft X rays – is of agreed synchrotron (S) origin; the other rises from hard X rays to the GeV band with occasional bursts up to the TeVs, and is of likely inverse Compton (IC) nature (for basics of radiative processes see Rybicki & Lightman 1979).

Detailed SED modeling (e.g., Cavaliere et al. 2017 hereafter CTV17, Table 1) confirms that both humps are produced when relativistic electrons with number densities $n \sim 10^3 \text{ cm}^{-3}$ interact with the jet magnetic fields $B \sim 1 \text{ G}$ to emit S radiation at frequencies $\gamma^2 eB/\text{mc}$, and produce from the source size $R \sim 5 \times 10^{16} \text{ cm}$ observed (isotropized) luminosities $L_S \propto n R^3 B^2 \Gamma^4$. Meanwhile, by IC in its S-Self Compton version (Maraschi et al. 1992) suited to BL Lacs, the relativistic electrons upscatter the very S photons to energies $\gamma^2$ times higher (full discussion is given, e.g., by Urry & Padovani 1995, Peterson 1997, Ghisellini 2010).

2. ANALYSIS OF UPDATED GAMMA-RAY DATA

The A15 analysis identified a quasi-periodic behavior of the gamma-ray emission of PG 1553+113 based on 4 main peaks. Their analysis spans the time window from July 2008 until July 2015. We extend the analysis to include the time interval up to September 2017. This additional 2-year stretch of data (shown in Fig. 1) provide important information to confirm the gamma-ray periodicity and add new clues. Details of the data analysis of Fermi-LAT data are provided in the Appendix A1.

As anticipated above, a new peak has occurred at the expected time based on the 2.18 year periodicity of A1. The updated set of data now provides a full 5-fold iteration of a main pattern comprising a prominent peak and a prolonged trough. We give in Fig. 1 the complete gamma-ray light curve with the new data marked in red color.

To analyze periodicity and additional features in the signal we used tools that do not refer to any sinusoidal pattern but rather adopt data folding and shifting (phase dispersion minimization, PDM, see Appendix A2) and projections onto a localized vectorial basis such as the continuous wavelet transform (CWT, see Appendix A3). Our results concerning PG 1553+113 are presented in Fig. 2 and in Figs. 3 - 4, respectively. We have checked the red noise properties of the gamma-ray data, and found they can be represented by a decreasing power-law with index $0.83 \pm 0.11$ consistent with A15. The related confidence levels are reported on Fig. 4. From our analysis we conclude that the main cyclic pattern is confirmed with a period $P \simeq 2.2$ years at a confidence level significantly greater than 99%.

On the other hand, we also detect a secondary pattern characterized by pairs of lower peaks (“twin peaks”) flanking the main ones as we discuss in Sect. 4. Such features are clearly pinned down by the CWT algorithm in most cycles, and especially at around MJDs 54800, 57550, and 57950 with increasing associated powers (see Fig. 3 and its caption). In fact, a close look at the gamma-ray curve in Fig. 1 (top panel) confirms these features, including their increasing amplitudes. Our Fig. 4 shows the CWT power obtained for two specific temporal sections. A first one during the cycle 3 without strong twin peak signal (black curve), and a second one during cycle 5 with a twin peak signal at confidence levels greater than 95% (red curve).

We mark in Fig. 1 by “a” and “b” the times of actual or expected occurrences of twin peaks, and discuss the phenomenon in Sect. 4. Such an updated and rich data set warrants a new and aimed discussion.

3. INTERPRETING THE MAIN PERIODIC PATTERN

We base our interpretations on the dynamics of a binary supermassive black hole (SMBH) system comprised of a mass $M_1 \sim 5 \times 10^{8} \text{M}_\odot$ and a companion of smaller mass $M_2 \sim M_1/10$, tracing closely Keplerian orbits around the center of mass at an average distance of a some parsecs (see A15).

A geometrical interpretation is based on periodic visibility within the $\theta \sim 5^\circ$ cone of jet emission, as detailed by Sobacchi et al. 2017. However, such a model not only is limited to the S radiation components, but also is constrained to describe the oscillations of a secondary jet $j_2$ launched by the smaller mass BH, lest fast dissipation of orbital energy into gravitational waves would cause early onset of orbital decay and catastrophic merging (same authors, their Eq. 28). But then, there is no trace in the data of the emission closely perpendicular to the orbital plane from the jet $j_1$ associated with the major component $M_1$; yet this ought to be dominant due to its higher accretion rate and luminosity, typically $L_1 \propto M_1$ in the Eddington regime.

Our interpretation (taking up from CTV17) is instead aimed at high-energy radiations and electrons, and instead centered on dynamically triggered evolution of the primary jet $j_1$ (see Fig. 5). We recall that in a blazar of the BL Lac type like PG 1553+113 such a jet with its intermediate magnetization $\sigma_j = B^2/4 \pi n m_e^2 \Gamma \sim 1$ (the ratio of magnetic and bulk kinetic energy densities in the observer frame) is metastable. Large scale, MHD instabilities are triggered by the varying gravitational force $F \propto 1/r^2$ exerted by $M_2$ from a distance $r$ (with $r \gtrsim r_2$ to within $0(r_1/r_2) = M_2/M_1 \ll 1$ along its Keplerian elliptical orbit with eccentricity $e \simeq 0.1$; specifically on a critical orbital arc around periastron that covers about 20% of the total (see Fig. 2 of CTV17).

Thus the magnetic B lines are compressed, distorted and twisted, and so made prone to collisionless tearing and reconnecting instabilities that proceed down to the kinetic level. Then the induced E fields accelerate electrons to energies that attain Lorentz factors $\gamma \sim 10^4$ for values of the local electron magnetization $\sigma_e \propto \sigma_j m_e^2/m_0 \gg 1$. Such a generic kind of evolution with its MHD - kinetic transition has been widely computed, discussed (see, e.g., Migone et al. 2013, Kagan et al. 2015, Striani et al. 2016, Yuan et al. 2016), and applied by Petroponoulou et al. 2016 to conditions expected.
to prevail in blazar jets.

Focusing on PG 1553+113, we argue that in fields $B \sim 1$ G the high energy electrons accelerated within the jet at heights around $10^{16}$ cm will emit S radiations from the optical to the keV X-ray band (and occasionally beyond); meanwhile, such photons are upscattered into the GeV range after the SSC radiation process. This view is in tune with the complex correlations gamma-ray – X-ray – optical present in the updated data (compare Figs. 1: top, middle, and bottom panels), once the following expected features are considered: optical and X-ray synchrotron emissions occurring in the axial $\mathbf{B}$ at increasing heights and photon energies $E \propto \gamma^2$ will be increasingly focused into angles of order $1/E^{1/2}$ at the single electron level that constrains from below the overall beam widths.

In fact, the optical emissions are observed to be quite smoother and broader when compared to the spiky X rays; the latter feature narrow high-energy surges (likely powered by fluctuations in the energy distribution tail) that may be easily missed. Instead, gamma rays from IC scattering cover a broad emission fan that can be continuously observed, and sometimes reach the VHE range (e.g., Aleksic et al. 2015).

We stress that the basic peak/trough pattern repeating itself throughout the gamma light curve of PG 1553+113 features a sharp aspect ratio, as expected from MHD - kinetic instabilities triggered by the gravitational force $F(r) \propto 1/r^2$ near periastron and then relaxed along the rest of the orbit. Whence we conclude that in the main pattern moderately variable amplitudes combine with precisely preserved timing to constitute the hallmark of jet plasma physics driven by binary dynamics as occurring in PG 1553+113.

4. THE SECONDARY TWIN PEAKS

We have anticipated in Sect. 2 the evidence we find in the updated gamma-ray data concerning twin secondary peaks that flank in a nearly symmetric disposition most main peaks of the basic periodic pattern, and last for some $10^2$ days.

Here we stress how extant such substructures are in cycle 5. Similar features also loom out with a lower amplitude near MJD 55000 at the very beginning of the Fermi-LAT observations that open cycle 1; then they come in full view in cycle 2 and in cycle 4. In all such instances their presence and quantitative parameters are strongly supported by our CWT analysis (see Fig. 3, 4 and their captions) in the form of elongated spots between about MJD 57000 and MJD 58000 with a time...
interval of $\sim 300$ days, that corresponds to the occurrence of twin peaks in the light curve.

In conclusion, the twin peaks appear with similar parameters in our analysis tools: light curves and CWT. Thus they call for an explanation. In the following, we discuss two possible ways toward understanding their production: a single-jet interpretation based on additional instabilities induced in the primary $j_1$; and a two-jet interpretation including the contribution of the independent relativistic jet $j_2$ launched by the secondary BH.

4.1. A single-jet interpretation

This interpretation is based on a development of the discussion in Sect. 3 concerning the origin of the main periodic pattern, to cover also existence and features of the twin peaks in the light curve of PG 1553+113. The basic driver is again identified in substantial magneto-gravitational stresses induced by the orbiting companion BH $M_2$ that induce strong perturbations in the structure of the main jet $j_1$ launched by $M_1$.

The process of producing the twin peak phenomenon has to explain the very presence of twin peaks in the gamma-ray light curve, and their approximate time symmetry relative to a main one. Other points to note are the correlation with X-ray spikes and the often enhanced states of optical emission.

The repetitive, yet not fully periodic, nature of the twin peaks suggests an interpretation in terms of an unstable source of additional emission that is superimposed to the mechanism underlying the main periodic pattern in gamma rays (and related optical emissions) associated with the main peaks. Here we emphasize that the gravitational perturbation of $j_1$ induced by the companion BH as it transits the critical orbital arc can produce a number of MHD transient structures. Fig 5 (left panel) provides an outline of the related configuration.

As the secondary BH of mass $M_2$ enters the critical arc, magneto-gravitational stresses are induced in $j_1$ and propagate longitudinally along the envelope of the magnetic helicoidal field threading the jet. Helicoidal and shear MHD modes (Buratti et al. 2012) can be induced by this process. This induces magnetic twisting and reconnections in $j_1$ as detailed in Sect. 3. The resulting tail of the electron energy distribution is enhanced by the presence of such an additional source of accelerations.

In closer detail, we estimate at $\kappa R_S \approx 10^{15}$ cm (in terms of the Schwarzschild radius $R_S \approx 10^{13}$ cm and of the factor $\kappa \sim 10^2$) the radius of the inner region of the accretion disk surrounding $M_1$ wherefrom the $j_1$ jet is launched. The gravitational force induced by $M_2$ on the plasma and magnetic structure of $j_1$ will enhance MHD shear modes with low azimuthal index $m$ that propagate along the jet axis. We note that the timescale for such propagation is bounded by $\Delta L/c$, where the Alfven velocity is close to $c$. We therefore obtain a coherence scale shorter than $10^2$ light-days corresponding to the width of the twin peaks for $\Delta L \sim 10^{17}$ cm, a natural scale for BL Lac jets.

Eventually, the additional MHD perturbation fades away, and the plasma column of $j_1$ relaxes to a lower energy state as typical of sub-critical plasma configurations perturbed by external drivers (for laboratory tests, see Buratti et al. 2012). In this interpretation, the secondary peak preceding the main peak is induced by the very entrance of the secondary BH in the critical orbital arc. The secondary peak following the main one is produced at the very end of the process, as the companion BH leaves the critical orbital arc and $j_1$ reverts back to its unperturbed state.

The effect of the external, transient perturbations is reflected in the X-ray range, where the S emission is dominated by top energy electrons. X-ray spikes observed in PG 1553+113 during cycles 4 and 5 are a likely product of the mechanism. Meanwhile, inverse Compton radiation from the same electron population produces the twin peaks in the gamma-ray range. We speculate that the radiative outcome may extend into the TeV range, as far as allowed by the Klein-Nishina cut off. The available optical light curve of PG 1553+113 (see A15 and Fig. 1, bottom panel) shows episodes of enhanced emission that correlate with the general trend of increased gamma rays, and features highs (if not flares) corresponding to twin peaks.

The potential importance of X-ray emissions in this context is stressed by the detection of X-ray flares correlated with the gamma-ray twin peaks of cycle 5, specifically at MJD $\sim 57530$ and 58000 (see Fig. 1, middle panel). In addition, despite the sparse X-ray monitoring of the source during cycles 1-4, a very prominent X-ray outburst near MJD 56050 was detected (with little gamma-ray response) at a phase typical of a twin peak.

Natural consequences of the process include: an intrinsically unstable behavior of the twin peak phenomenon in the gamma-ray range, as caused by the turbulent nature of the driving MHD instability; X-ray outbursts corresponding to maxima of twin peaks of similar strength as for the main peaks (see cycle 5), and the secondary peak episode in cycle 4; lack of systematic correlation between optical highs and X-ray outbursts.

The last point is important for BL Lacs. Indeed, lack of correlation between the X-ray and optical emissions has been often observed in several such sources such as Mrk 421 (Baloković et al. 2016). In the present case, the periodic nature of PG 1553+113 provides the first evidence for a prime driver of electron acceleration whose recurrent pattern can be used to model the properties of relativistic jets of BL Lac blazars.

4.2. Two-jet interpretation

We now consider a two-jet interpretation based on emissions also from the jet $j_2$ associated with the secondary BH (see Fig. 5, right panel). An origin in $j_2$ of the twin peaks is indicated by their specific features relative to the central main peak: the definitely lower amplitudes by a ratio about 1/2 or less; the lack of detailed amplitude correlation with the main peak’s; their own, shallow peak/trough pattern.

The first feature constitutes the positive, telling side of what we noted in Sect.3; namely, a weaker accretion power is available for twins from the lower accretion rates prevailing at the base of the secondary jet $j_2$. In fact, the power will scale as $L_a \propto L_\gamma \propto M_2 \ll M_1$.

The second and third features relate in the present view to the specific trigger of the twins’ emissions. They would be produced not directly by the shear gravitational
force from $M_1$, but rather by the torque $T$ constituted by the latter coupled with jet base reaction. This is because a torque’s action is due to be smoother, since it is proportional to $T(r) \propto r F(r) \propto 1/r$.

In detail, the vectorial torque acting on the mass $m_2$ of the secondary jet is given by $T = F \times \ell$ in terms of the gravity force $F = G m_2 M_1/r^2$ with its lever arm $\ell$, induced by the massive companion and dominating the local gravity proportional to $M_2/\ell^2$. The modulus $F \ell \sin \Theta$ includes an angular factor that may be approximated as $\sin \Theta \simeq r/\ell$ for $r/\ell < 1$. This implies a softer change of dynamical stress along the orbit caused by the torque $T(r) \propto 1/r$, resulting in a smoother peak/trough secondary pattern than could arise from the force itself.

On the other hand, the maxima of the twin peaks $a$ and $b$ occur at a time distance $\Delta t_a$ and $\Delta t_b$ from their central main peak at $t_i$, and outside its half-width $\delta t_i$. The observed nearly symmetric locations $\Delta t_a \simeq \Delta t_b > \delta t_i$ (as indicated on Fig. 1, top panel) call for a torque action with maxima not really simultaneous to the maximal force, yet inducing $j_2$ visibility close to the beginning and the end of the strong-force range around periastron, see Sect. 4.

Guided by such a detailed observational evidence, we submit that the torque specifically causes $j_2$ to bend/release into/out the visibility cone, while also triggering the jet’s internal instabilities as discussed in Sect. 2. Note that our interpretation implies that a twin member can appear close to a main peak both on its ascending and descending shoulder, as in fact observed.

Next, we discuss key parameters and quantitative relations in the light of a simple model for $j_2$: here a toy-top of substantial angular momentum and high angular velocity $\omega$ (limited only by $c/2\pi R_{S2} \simeq 5 \times 10^{-3} \text{s}^{-1}$, in terms of the Schwarzschild radius $R_{S2} \sim 10^{12} \text{cm} \times M_2$) undergoes a slow precessional rotation with velocity $\omega_p \ll \omega$ under the action of a torque (see Fig. 5-5 in Goldstein [1959]). When averaged over nutations, the dynamics of rigid bodies yields the precessional velocity in the simple form (cfr. Goldstein [1959])

$$\omega_p = T/\omega I_2,$$

in terms of the torque $T$ divided by the angular momentum $\omega I_2$, given the moment of inertia $I_2 \propto m_2 R_{S2}^2$; in fact, $m_2$ cancels out between $I_2$ and $T$.

In our binary system, an orbital phase depending torque $T$ is provided by the gravitational action from $M_1$ coupled with the opposite reaction from the $j_2$ base. The latter is likely constituted (similarly to the $j_1$ structure discussed in Sect. 4.1 above) by a central disk region with radius $\kappa R_{S2}$ larger than $R_{S2}$ by a factor $\kappa \sim 10^2$. Then $I_2$ scales up by the factor $\kappa^4 \sim 10^8$; this helps to achieve a substantial angular momentum in a standard “proton-loaded” jet with total density of some $10^5 \text{cm}^{-3}$ and radiative efficiency around 5% (cf. Celotti & Ghisellini 2008).

Our main point is as follows. If just a few precessional rotations occur (as if close to a resonance) over the strong interaction arc that takes some 10% of the orbital period around the periastron, we expect $\omega_p \approx 10\omega_0$ (still $\ll \omega_0$) to hold for the precessional in terms of the orbital frequency. Again barring nutations, this translates into the approximate values

$$\Delta t_a \approx \Delta t_b \approx P/10 \simeq 3 \text{ months},$$

in agreement with the observed spacing of the twin peaks in the light curve. The precession provides a dynamical memory that enforces twin peaks symmetry and also causes smooth amplitude changes from cycle to cycle.

We add that closer insights into $I_2$ (that is, structural information concerning jet and disk of the minor companion) may be obtained from the bounds on $\omega$ that...
Fig. 3.— CWT (Continuous Wavelet Transform) synoptic map based on the standard Morlet 6 wavelet, of period and spectral power versus time of the Fermi-LAT data concerning PG 1553+113 from 2008 August 4 to 2017 September 4. The power spectrum shows an extant stripe at normalized amplitudes around 650 that supports the main periodicity of $P \approx 2.2$ yr. It also shows spots at amplitudes around 140 and lower, at times around MJD $\approx 55300$, $57200$, $57700$ related to secondary structures. In fact, looking into the updated gamma-ray light curve of Fig. 1 (top panel), a closely repetitive secondary feature is recognized in cycles 2, 4, and 5 in the form of twin peaks flanking the main one at times around $\Delta t \approx \pm 250$ d. The two vertical lines correspond to the time sections used for the analysis reported in Fig. 4.

Fig. 4.— The CWT power of the gamma-ray lightcurve determined for two time sections (as highlighted in Fig. 3). The black curve shows the power for a time section in cycle 3 selected for the absence of twin peaks. The red curve provides the wavelet power for a time section in cycle 5 where the twin peaks phenomenon is strongest. Dashed curves show specific confidence levels obtained from red noise with power law index 0.83 (see Sect. 2).
scale with $M_1$ and $M_2$ to read
\[ \omega < c/2\pi R_{S2} \propto 1/M_2, \quad \omega > \omega_{\text{min}} \propto M_1^{1/3}/M_2 P^{1/3}. \]
Here we have used Eq. 1, $T \propto M_1/r$, $I_2 \propto R_{S2}^2$ as said above, and the $3^{rd}$ Kepler’s law in the form $r \propto M_1^{1/3}/P^{2/3}$.

Clearly, deviations from rigidity are expected, and might cause wide variance of the above values. Actually, the data in Fig. 1 (top panel) show the twin peaks to have undergone just a slow amplitude increase over the last few periods, yet preserving good permanence of their relative timing $\Delta t_\text{g} \approx \Delta t_\text{b}$. Such a behavior apparently constitutes yet another instance of the general trend: timing permanence vs. limited amplitude variations, that marks jet plasmas affected by overall binary dynamics as noted at the end of Sect. 3.

5. CONCLUSIONS

The data concerning the emissions of PG 1553+113 as updated toward present confirm the periodic behavior looming out in A15, and add considerable new information. The updated light curves warrant close analyses as we carried out in Sect. 2, and detailed interpretations as we discussed in the rest of the present paper.

Sect. 3 took up from CTV17 to address the origin of the main, periodic peaks now observed throughout full 5 cycles in the updated light curve of PG 1553+113 ($z \simeq 0.5$), and to trace them back to the dynamics of a binary SMBH system. Specifically, the main jet $j_1$ is periodically stressed by the gravitational force from the smaller mass BH, as the latter covers a critical orbital arc (some 20% of the orbit) across the periastron.

The stress destabilizes the sensitive BL Lac-type main jet $j_1$, by itself in a metastable condition due to its relatively large magnetization. The instability starts on large, MHD scales, then progresses into the collisionless kinetic regime and accelerates electrons to relativistic energies. These power non-thermal radiations, namely, synchrotron in the O, X bands and inverse Compton in gamma rays. The repetitive stress/release process produces the main periodic pattern comprising a high peak and a long trough, apparent throughout the gamma-ray light curve.

But we also found that the latter features secondary twin peaks flanking the main peaks. The twin peaks are marked by lower and varying amplitudes and by flickers uncorrelated with the main peak’s, but also show a relatively stable timing and a smoother peak/trough pattern.

The sparing single-jet interpretation in Sect. 4.1 (see Fig. 5, left panel) envisaged twin peaks to be produced again in $j_1$ at the very entering and exiting times of the secondary BH in the orbital arc of strongest stress. The response of its heliocoidal, magnetized plasma structure induces additional sheared reconnections and particle acceleration. After onset, the optical, X-ray and gamma-ray emissions persist for a duration comparable to the coherent propagation time (a few months) of the unstable modes along the jet axis. The plasma column eventually relaxes back to a lower energy state, with no appreciably enhanced gamma or X rays. Here the phenomena are turbulent in nature; expected outcomes include erratic amplitudes and shifting locations of the twin peaks, yet still flanking a main peak and preserving a recognizable time distance.

On the other hand, the two-jet interpretation of Sect. 4.2 took to heart all the above clues concerning timing, amplitudes and pattern of the twin peaks, and proposed that a similar stress/release process affects also the jet $j_2$ carried by the smaller binary companion. However, here the stress takes the specific form of a gravitational torque exerted by the dominant BH during the critical orbital arc across the periastron. Instability, accelerations and emissions will ensue much as in $j_1$, but for the reduced amplitudes related to the lower accretion rates that feed $j_2$.

Meanwhile, the same torque also causes the latter to slowly precede around an axis nearly perpendicular to the orbital plane. So $j_2$ meets the visibility condition (see Fig. 5, right panel) at an axial inclination $i < \theta \simeq 1/2$: this occurs on entering the critical orbital arc, and again on exiting it after about one precessional period. The combined process produces twin minor, closely symmetric peaks flanking the main peak at a time distance around several months, with slow amplitude drift. Occasionally, the nutations hitherto averaged out emerge and drive the emission out of the narrow visibility range, so that the observer misses a twin peaks event, as apparently occurred in cycle 3. Along this line, we proposed that the gravitational force setting the orbital dynamics also destabilizes the main jet $j_1$ along a short arc across the periastron, so triggering electron accelerations with associated S and IC radiations. Meanwhile, on board the smaller companion $M_2$ the related torque may affect the secondary accretion disk and jet $j_2$. Thus the latter is induced to emit its own, weaker radiations, and also to slowly precess and direct them in and out the narrow angular range of visibility.

Overall, we suggest that the binary dynamics drives the processes originated in the jets associated with either binary component into phase permanence and amplitude shifts. Single-jet vs. two-jet interpretations of twin peaks predict erratic changes vs. smooth amplitude shifts from cycle to cycle. In this light, it will be rewarding to keep under close watch the data evolution from PG 1553+113 over the next few years. In fact, repeated and shifting twin peaks superposed onto the main peak/trough pattern in its gamma-ray light curves may well limit the formal confidence in simply periodic behavior that can be obtained from any analytical tool. On the other hand, evidence of two jets will directly provide a double signature for the binary nature of the SM system underlying the repetitive emissions of this blazar. Such a signature would bypass the often contentious issue of red noise contaminating many searches for other periodic blazars, see discussion in Sandinelli et al. (2017); see also Zhang et al. (2017) and Prokhorov & Moraghan (2017) who agree with CTV17 on giving PG 1553+113 the standing of a currently primary candidate.

The importance of finding binary SMBHs in general has been widely discussed in recent literature since the pioneering work by Begelman et al. (1980) to name just a few, we refer to Colpi (2014) and Volonteri et al. (2016) and Klein et al. (2016) and Amaro-Seoane et al. (2017) Here we stress the wide import of establishing even a single, relatively nearby and bright binary blazar. This would also im-
Fig. 5.—Left panel: schematic view of the SMBH binary PG 1553+113 according to the one-jet interpretation in Sect. 4.1. Right panel: view of the SMBH according to the two-jet interpretation in Sect. 4.2. The symbol ★ marks the orbital position wherefrom the main peak is emitted, whereas the symbols ‡, § mark the positions wherefrom the twin peaks are emitted. The jets outflow with velocities $v = c (1 - 1/\Gamma)^{1/2}$.

ply (see Sect. 1) outside the aperture of their e.m. jets many more misaligned and unconspicuous BL Lac candidates at comparable redshifts, even though only a fraction would be binaries at interesting stages of orbital evolution. Thus even one established binary blazar will constitute a long stride toward understanding birth and evolution of a class of similar systems, and setting targets to plan searches of low frequency and large amplitude gravitational waves in the developing project LISA.

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APPENDIX

1. FERMI-LAT DATA ANALYSIS

For the purpose of this work, we used the Science Tools provided by the Fermi satellite team\(^6\) on the Pass8 data around the position of PG 1553+113. The version of the Science Tools used was v10r0p5 with the standard \(P8R2\_SOURCE\_E\_V6\) instrument response function (IRF). The reader is referred to Fermi instruments publications for further details about IRFs and other calibration details (Ackermann et al. 2012).

We have adopted the current Galactic diffuse emission model (\(gll\_iem\_v06\_fits\)) in a likelihood analysis and \(iso\_P8R2\_SOURCE\_V6\_v06\_txt\) as the isotropic model; the FERMI 3rd Point Source Catalog \(gll\_psc\_v16\_fit\) (Acero et al. 2015) has also been used\(^7\). In modelling the data, the galactic background and diffuse components remained fixed. We selected Pass8 FRONT and BACK transient class events with energies between 0.1 and 300 GeV. Among them, we limited the reconstructed zenith angle to be less than 105° to greatly reduce gamma rays coming from the limb of the Earth’s atmosphere. We selected the good time intervals of the observations by excluding events that were taken while the instrument rocking angle was larger than 50°.

For our source PG 1553-113 we adopted a power-law model, and used the \texttt{make3FGLxml.py} tool to obtain a model for the sources within 25° region of interest (ROI). To analyze the data we used the user contributed package \texttt{Enrico}\(^8\).

We divided each analysis in two steps: in the first one we leave free all parameters of all sources within a 10° ROI, while the sources outside this ROI up to 25° have their parameters fixed. Then we run a likelihood analysis using the Minuit optimizer to determine the spectral-fit parameters and obtain a fit for all these sources. In the second step, we fix all the parameters of the sources to the fitted values, except for our source of interest, and run again the likelihood analysis with the Newminuit optimizer to obtain a refined fit. At all times, for the central target source PG 1553-113 we kept the spectral normalization free.

We analyzed the data from the whole Fermi/LAT mission, starting from 2008-08-04 15:43:36 UTC until 2017-10-04 00:00:00 UTC. For the purposes of this work and comparison with Ackermann et al. 2015, we produced a lightcurve by dividing the whole dataset into 20-day bins. The analysis was carried out using the assumptions made in this work, and we fixed the photon index at the value 1.604.

We obtained results compatible with those by A15, and produced new light curve points beyond the ones given in that work.

2. PHASE DISPERSION MINIMIZATION

To look for periodicity in the Fermi/LAT data we used the Phase Dispersion Minimization (PDM) method (Stellingwerf 2006). This computes the variance of the amplitude on each bin of a data sample. The overall variance of the data set is compared to the bin variances; if a true period is found, the ratio between the bin and the total variances will be small, whereas for a false period this ratio would be of order 1. This method has the advantage of being effective regardless of the shape of the possible period, as it is not based onto Fourier transforms of the data. A plot of the amplitude versus the trial period will show the true period in the form of a deep minimum in the plot.

To assess the significance of the period, we used the method by Linnell Nemec & Nemec 1985, which is based on Fisher’s Method of Randomization. In our case, PDM gives us a best period for our data set of \(P = 795.6 \pm 10.0\) days (2.18 ± 0.03 years).

3. CONTINUOUS WAVELET TRANSFORM

The Continuous Wavelet Transform (CWT) of the Fermi-LAT light curve reported as a power spectrum in Fig. 3 has been calculated using the IDL procedure \texttt{wavelet.pro} provided by Torrence & Compo 1998 and available at URL: \url{http://paos.colorado.edu/research/wavelets/}. In Fig. 3 we report the map we find in the space: time - period - spectral power (colors).

\(^6\) \url{http://fermi.gsfc.nasa.gov}
\(^7\) \url{http://fermi.gsfc.nasa.gov/ssc/data/access/}
\(^8\) \url{https://github.com/gammapy/enrico/}