Secondary period in the optical flux variations of the blazar PG 1553+113

B. Mihov, L. Slavcheva-Mihova

Institute of Astronomy and NAO, Bulgarian Academy of Sciences

Abstract. PG 1553+113 is among the few blazars whose flux variability is claimed to be periodic. The first hint for periodicity comes from Ackermann et al. (2015) – they found a 2.18 ± 0.08 years period in the Fermi/LAT *γ*-ray light curve of the blazar. This period was then confirmed by a number of authors and it was generally attributed to a precession of the binary supermassive black hole system.

We compiled the historical *VR* light curves of PG 1553+113 in the time interval from 2005 to 2019 and found a period in consistence with the above one (Agarwal et al. 2021). After correction of the light curves for the long-term variations, we were able to detect a secondary period of about 210 days in both bands. Similar results were reported by Sandrinelli et al. (2018): 250 ± 60 days. To improve the accuracy of the periods, we added new data sets to the used ones. We modeled the secondary periodicity in the historical *VR* light curves, assuming a helical jet geometry, and estimated the jet geometric parameters, namely viewing angle and pitch angle of the spiral motion and helical field.

1. Introduction

The BL Lac object PG 1553+113 was discovered in the course of the Palomar-Green survey of UV-excess stellar objects (Green et al. 1986). Due to its featureless spectrum, typical for BL Lacs (Falomo & Treves 1990), alternative techniques were applied to derive the redshift of about 0.433 (Johnson et al. 2019, Dorigo Jones et al. 2022). Agarwal et al. 2021; hereafter A21) found a low duty cycle of less than 18% based on the analysis of 74 intra-night monitoring sessions.

PG 1553+113 is among the few blazars whose flux variability is claimed to be periodic. The first hint for periodicity comes from Ackermann et al. (2015) – they found a 2.18 ± 0.08 yr period analysing the Fermi/LAT *γ*-ray light curve of the blazar. This period was then confirmed by a number of authors in the *γ*-rays and in the optical (e.g. A21 and references therein) and it was generally attributed to the precession of the binary supermassive black hole system (e.g. Huang et al. 2021 and references therein).

A21 have built and studied the historical *VR* light curves of PG 1553+113 covering a time interval from 2005 to 2019 and confirmed the above period. After accounting for the two-year periodicty on the *VR* light curves, the authors were able to detect a secondary period of about 210 days in both bands. A similar period in the optical was found by Sandrinelli et al. (2018): 250 ± 60 d.

In this study we improve the estimation of the above periods adding new data sets to the already used ones and model the secondary periodicity in the corrected historical *VR* light curves assuming a helical jet geometry.

2. Data analysis

We built the historical *VR* light curves of PG 1553+113 from April 2005 to February 2022 extending the set of data sources of A21 as follows:

1. We added *V* band observations performed by the Swift's Ultraviolet/Optical Telescope (Roming et al. 2005). We used only the observations from September 2018 to September 2019, which encompass the April 2019 flare (see A21 for details about the flare);

2. We extended the All-Sky Automated Survey for Supernovae (Shappee et al. 2014; Kochanek et al. 2017; Jayasinghe et al. 2019) data set with new *V* band observations; we now included the *g* band observations;

3. We extended the Zwicky Transient Facility (Masci et al. 2019) data set with new *gr* band observations.

We added an intra-night monitoring in the *R* band taken on May 7, 2010 with the 50/70-cm Schmidt telescope of Rozhen NAO (plus an estimate in the *BVI* bands). The optical photometric sequence is that one published in Raiteri et al. (2015); the star #2 is used as a control star. The light curves of PG 1553+113 and of star #2 are shown in Fig. 1 – the lack of intra-night variability is obvious. This lack was also confirmed by the scaled *C*-criterion applied following Mihov & Slavcheva-Mihova (2019): we got C = 1.220, less than 2.576, the value needed for variability at 99.5% confidence level.

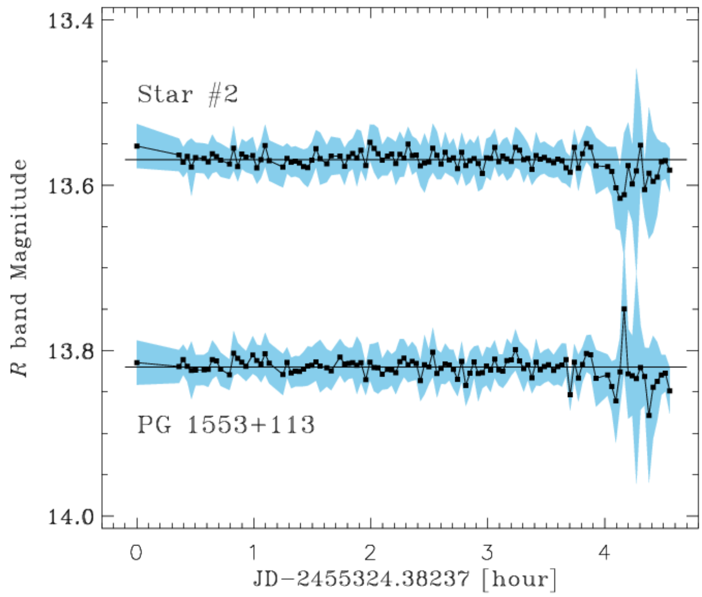

Fig. 1: *Intra-night R band light curves of PG 1553+113 and of the control star for May 7, 2010. The shaded region represents the observational uncertainties and the horizontal lines mark the corresponding weighted mean magnitudes: for the star #2 it equals to 13.569 ± 0.002 (s.d. 0.009).*

The VR data sets were adjusted (if needed) to the A21 ones and then combined. Data sets in g band were combined without adjusting. Using 12 data points taken in one and the same night among the combined gVR band data sets and the single r band one, we fit the equations

$$V\text{–}g = k_{0g} + k_{1g}(g\text{–}r) \quad \text{and} \quad R\text{–}r = k_{0r} + k_{1r}(g\text{–}r).$$

Using these equations, we transformed the gr magnitudes to the VR bands and then added them to the master VR data sets. The resulting VR light curves are shown in Fig. 2, upper panel.

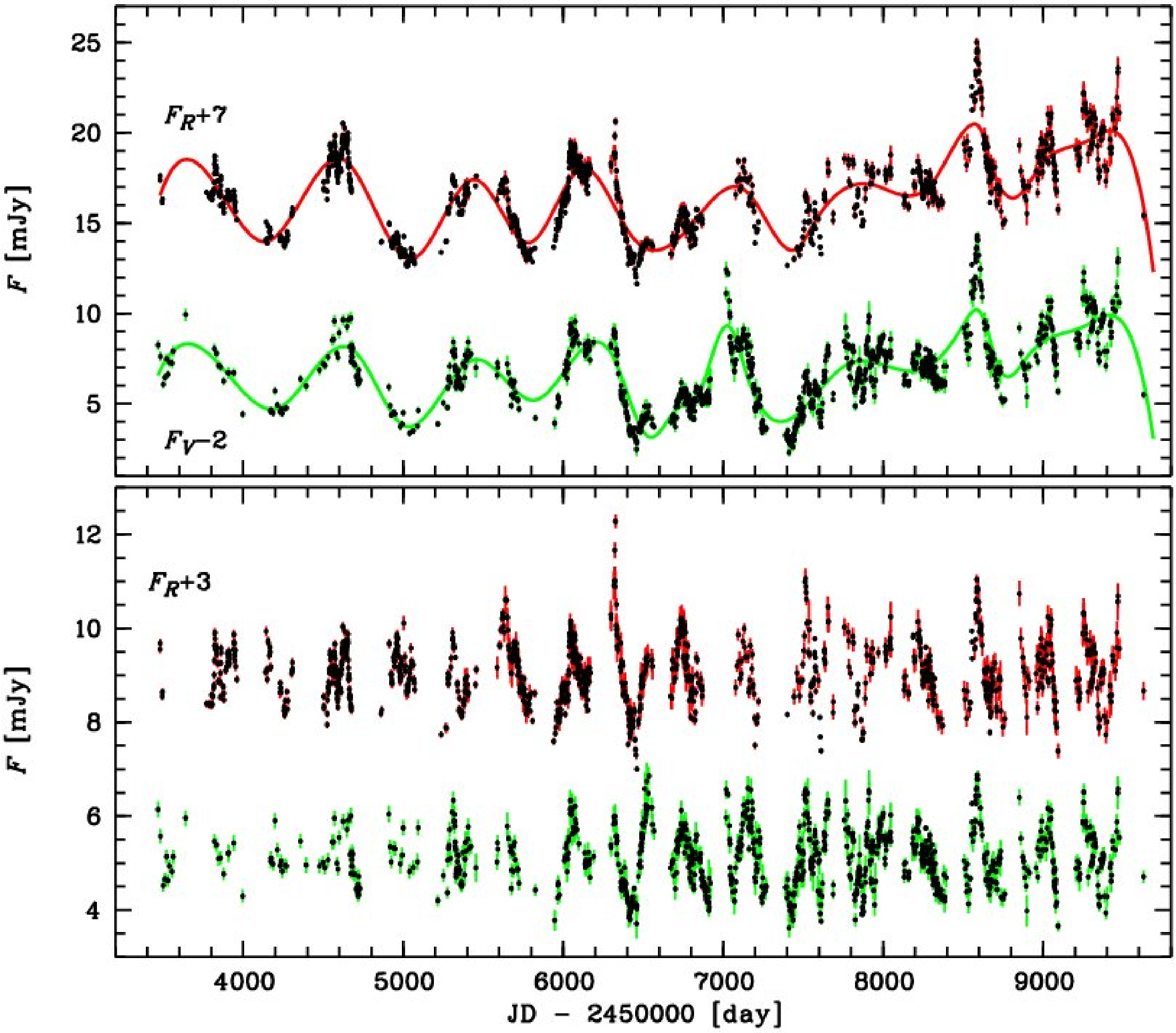

Fig. 2: *Upper panel: historical VR band light curves for PG 1553+113. The cubic splines, fitted through the corresponding 10 day binned light curves, are overplotted (V band – green line, R band – red line). Lower panel: historical VR band light curves corrected for the long-term variations.*

The inspection of Fig. 2 suggests the presence of at least two variable components – a long-term one, responsible for the quasi-periodic behaviour of PG 1553+113 and a short-term one producing the flux variations onto the top of the long-term component. Therefore, to study the short-term variations in details one should remove the long-term component. This was done following Villata et al. (2002, 2004) under the assumption that the long-term variations are caused by the Doppler factor change; that assumption is justified on the base of the non-significant bluer-when-brighter trend obtained by A21. The fitted splines are shown in Fig. 2, upper panel, and the corrected light curves are shown in Fig. 2, lower panel.

3. Results and Discussion

We present the results from the photometric study of the blazar PG 1553+113 using mainly archival data. This is a continuation of our work started in A21.

Applying the standard Lomb-Scargle periodicity search technique, we obtained the following periods for the *VR* light curves: 779.9 ± 66.3 d (2.14 ± 0.18 yr) and 788.3 ± 60.3 d (2.16 ± 0.17 yr), respectively. The fitting of the *VR* splines with a sine wave function resulted in periods of 797.4 +/- ±6 d (2.18 ± 0.07 yr) and 800.4 ± 29.2 d (2.19 ± 0.08 yr), respectively. The periods found are equal to within the quoted uncertainties to those reporeted by A21; however are systematically lower. This difference could refelect the shape of the newly added parts of the light curves. The inspection of the spline fits reveals two segments of the long-term light curves that have different behaviour regarding the periodicity (see Fig. 2). The first segment (up to about JD 2457400) clearly shows periodic variations, while the periodicity in the second one is not so obvious. In this regard further observations of dense time coverage are needed to follow the light variations in the second segment in details.

After correction for Doppler factor variations, we got the following *VR* periods: 208.9 ± 4.8 d and 211.3 ± 4.0 d, respectively. These results are consistent with those reported in A21. The secondary periodicity was interpreted by us as being due to the helical motion in the precessing jet. Following Sarkar et al. (2021) we fitted the *R* band light curve (as being more dense) with a helical model having a period of 211.3 d. We got a pitch angle of the helix of 3° and the angle of the axis of the jet with respect to the line of sight of 1°. The fit is shown in Fig. 3.

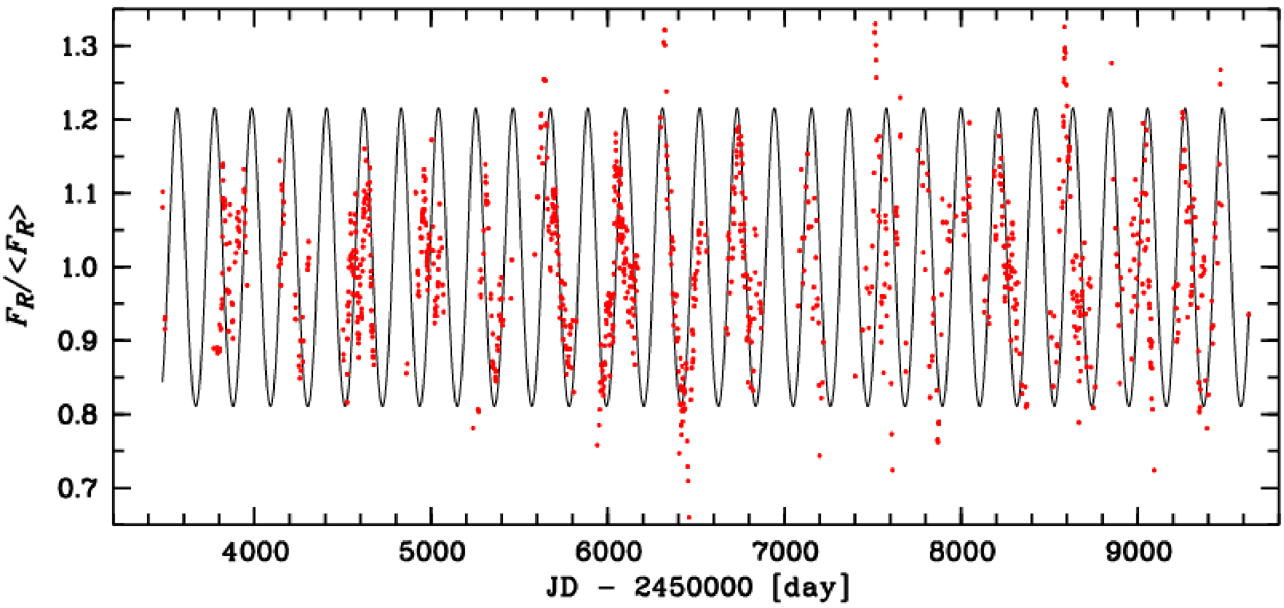

Fig. 3: *R band light curve (dots) fitted by a helical model (solid line).*

Furthermore, we added one more night of intra-night monitoring to the nights described in A21. We obtained no variability during that night and so, we can update the PG 1553+113 duty cycle to 17.3% and 10.7% depending on whether the probably variable cases are considered variable or not, respectively.

Acknowledgements and References

This research is based on activities partially supported by the Bulgarian National Science Fund under contract DN 18/13-12.12.2017.

Ackermann, M., Ajello, M., Albert, A., et al. 2015, ApJL, 813, L41

Agarwal, A., Mihov, B., Andruchow, I., et al. 2021, A&A, 645, A137 (A21)

Dorigo Jones, J., Johnson, S. D., Muzahid, S., et al. 2022, MNRAS, 509, 4330

Falomo, R. and Treves, A. 1990, PASP, 102, 1120

Green, R. F., Schmidt, M., and Liebert, J. 1986, ApJS, 61, 305

Huang, S., Yin, H., Hu, S., et al. 2021, ApJ, 922, 222

Jayasinghe, T., Stanek, K. Z., Kochanek, C. S., et al. 2019, MNRAS, 485, 961

Johnson, S. D., Mulchaey, J. S., Chen, H.-W., et al. 2019, ApJL, 884, L31

Kochanek, C. S., Shappee, B. J., Stanek, K. Z., et al. 2017, PASP, 129, 104502

Masci, F. J., Laher, R. R., Rusholme, B., et al. 2019, PASP, 131, 018003

Mihov, B. and Slavcheva-Mihova, L. 2019, in American Institute of Physics Conference Series, Vol. 2075, 10th Jubilee International Conference of the Balkan Physical Union, 090020

Raiteri, C. M., Stamerra, A., Villata, M., et al. 2015, MNRAS, 454, 353

Roming, P. W. A., Kennedy, T. E., Mason, K. O., et al. 2005, SSRv, 120, 95

Sandrinelli, A., Covino, S., Treves, A., et al. 2018, A&A, 615, A118

Sarkar, A., Gupta, A. C., Chitnis, V. R., and Wiita, P. J. 2021, MNRAS, 501, 50

Shappee, B. J., Prieto, J. L., Grupe, D., et al. 2014, ApJ, 788, 48

Villata, M., Raiteri, C. M., Kurtanidze, O. M., et al. 2004, A&A, 421, 103

Villata, M., Raiteri, C. M., Kurtanidze, O. M., et al. 2002, A&A, 390, 407

Zibecchi, L., Andruchow, I., Cellone, S. A., and Carpintero, D. D. 2020, MNRAS, 498, 3013

Zibecchi, L., Andruchow, I., Cellone, S. A., et al. 2017, MNRAS, 467, 340