Possible Gravitational Microlensing Events in the Optical Lightcurve of Active Galaxy S5 0716+714

D. L. Król1, L. Stawarz1, J. Krzesinski1, and C. C. Cheung2

1 Astronomical Observatory of the Jagiellonian University, Orla 171, 30-244 Kraków, Poland; DKrol@oa.uj.edu.pl
2 Naval Research Laboratory, Space Science Division, Washington, DC 20375, USA

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Abstract

A well-known active galaxy of the blazar type, S5 0716+714, is characterized by a particularly high-variability duty cycle on short timescales at optical frequencies. As such, the source was subjected to numerous monitoring programs, including both ground-based as well as spaceborne telescopes. On closer inspection of the most recent accumulation of the data provided by the Transiting Exoplanet Survey Satellite, we have noticed several conspicuous events with “volcano-like” symmetric shape, all lasting for several hours, which closely resemble the achromatic events detected with the previous Whole Earth Blazar Telescope campaigns targeting the source. We propose that those peculiar features could be due to the gravitational microlensing of the innermost segments of the precessing jet in the system by a binary lens. We study the magnification pattern of the lens with the inverse-ray shooting method and the source trajectory parameters with the Python package MULENSMODEL. In this way, we were able to fit successfully all the selected events with a single lens, adjusting slightly only the source trajectory parameters for each lensing event. Based on the fit results, we postulate the presence of a massive binary lens containing an intermediate-mass black hole, possibly even a supermassive one, and a much less massive companion (by a factor of $\lesssim 0.01$) located within the host galaxy of the blazar, most likely the central kiloparsec region. We discuss the major physical implications of the proposed scenario regarding the quest for the intermediate-mass and dual supermassive black holes in active galaxies.

Unified Astronomy Thesaurus concepts: Black holes (162); Gravitational lensing (670); Active galaxies (17); Blazars (164); Active galactic nuclei (16)

1. Introduction

Gravitational lensing has wide application in cosmology and astrophysics (for reviews, see, e.g., Blandford & Narayan 1992; Narayan & Bartelmann 1996). Among many others, it was proposed that microlensing can possibly explain at least some part of the variability of active galactic nuclei (AGNs), in particular the achromatic, very short-timescale flux changes in blazar sources (e.g., Subramanian et al. 1985; Schneider & Weiss 1987; Gopal-Krishna 1991; for a review, see Wambsganss 2006). Lately, this idea has been somewhat resurrected by Vedantham et al. (2017) and Peirson et al. (2022), who proposed that the peculiar yearlong features in the radio lightcurve of blazar J1415+1320, consisting of a symmetric double-horn minimum (designated by the authors as a “volcano-type” shape event), could be explained by “milli-lensing” events involving a binary lens.

Two-point-mass lensing is a well-understood phenomenon (Schneider & Weiss 1986). For example, gravitational lensing by a binary star leading to the double-horn shape in the lightcurve of a lensed source has been discussed by Mao & Paczynski (1991) in the specific context of Galactic stars and planets. The authors pointed out that when the source is projected close to the caustics, an extra pair of unresolved microimages is formed, creating complicated patterns in the source lightcurves, including the characteristic double-horn features.

In this paper, we present another take on the story. Namely, we identify peculiar symmetric features in the optical light-curve of the blazar S5 0716+714, lasting for several hours each, with similar double-horn flux profiles. We propose that all of these could in fact be due to the lensing of the innermost segments of the precessing jet in the source by a binary lens consisting of an intermediate-mass black hole (IMBH) or even a supermassive-mass black hole (SMBH) with a less massive companion (mass ratio $\lesssim 0.01$) located within the host galaxy of the blazar.

S5 0716+714 is a very well-known blazar located at redshift $0.227 < z < 0.254$ (Dorigo Jones et al. 2022). For modern cosmology with $H_0 = 70 \, \text{km} \, \text{s}^{-1} \, \text{Mpc}^{-1}$, $\Omega_m = 0.3$, and $\Omega_{\Lambda} = 0.7$, this corresponds to angular-size distance of $d_A \approx (0.75 - 0.82) \, \text{Gpc}$ and conversion scale of $(3.64 - 3.96) \, \text{kpc} \, \text{arcsec}^{-1}$. The blazar is characterized by a particularly high duty cycle on short timescales at optical frequencies and as such was subjected to numerous intranight monitoring programs, including several campaigns on behalf of the Whole Earth Blazar Telescope (WEBT) Collaboration (e.g., Ostorero et al. 2006; Bhatta 2016), and most recently with the Transiting Exoplanet Survey Satellite (TESS) by Raiteri et al. (2021).

On closer inspection of the most recent TESS lightcurves of the target, we have noticed at least six several-hours-long conspicuous events, whose “volcano-like” symmetric shape resembled the features discussed by Vedantham et al. (2017) and Peirson et al. (2022) in the radio lightcurve of J1415 +1320. We note, however, that the J1415+1320 radio events are much longer, lasting up to even a few years. Interestingly,
the identified TESS events resemble closely achromatic features detected previously in the source optical lightcurve with WEBT (Bhatta 2016). As we argue below, all of those could be explained in the framework of the microlensing scenario.

2. TESS Data

For our analysis, we use short-cadence (120 s) TESS mission (Ricker et al. 2015) data for S5 0716+714 (TESS Input Catalog source, TIC 147796121) downloaded from the Barbara A. Mikulski Archive for Space Telescopes. The target was observed in four seasons:

1. 2019-12-25–2020-01-20, sector 20, camera 2, ccd 2
2. 2020-06-09–2020-07-4, sector 26, camera 4, ccd 4
3. 2021-06-25–2021-07-23, sector 40, camera 4, ccd 3
4. 2022-01-01–2022-01-27, sector 47, camera 2, ccd 2

corresponding to the four panels of Figure 1. We adopted BTJD = BJD–2457000. Only the first observational season was the subject of the detailed analysis by Raiteri et al. (2021).

The Target Pixel Files data (containing the original CCD time series data in the shape of postage stamp image cutouts) from all the seasons were checked for possible field stars that could fall within the apertures/masks used by the TESS Science Processing Operations Center pipeline (TESS-pipeline) to extract the lightcurves.

S5 0716+714 appears to be a well-isolated object, and only faint (>19 mag) field stars can be found in the TESS-pipeline masks. This is confirmed by the CROWDSAP factor (describing the amount of light in the aperture attributed to the target object), which is between 0.962 and 0.982 in all observing seasons. A small but negligible light contamination comes from neighboring bright stars outside of the TESS-pipeline masks. Therefore, for further analysis, we used Pre-search Data Conditioning Simple Aperture Photometry fluxes (systematics-corrected photometry using cotrending basis vectors), which are lightcurves prepared by the TESS-pipeline. The TESS fluxes $F$ were converted to $R$-band magnitudes following Raiteri et al. (2021), namely $m_R^{\text{TESS}} = -2.5 \log F + 20.42$. For all subsequent analyses, we binned the data in 10 minute intervals. The resulting lightcurves of S5 0716+714 are presented in the four panels of Figure 1.

After a close inspection of the acquired TESS lightcurves, we found six notable events displaying symmetric double-horn minima. In fact, these lightcurve shapes resemble events previously found in ground-based WEBT campaigns in 2003 (Ostorero et al. 2006) and 2014 (Bhatta 2016), where “for about 6 hr (…) the source suddenly exhibited a strongly reduced level of flux variability, resulting in a plateau in all four bands’ light curves” (Bhatta 2016, Section 3.1.4 therein). One of the selected TESS events, with the superimposed WEBT 2003 and 2014 events (shifted vertically by $-1.45 \text{mag}$ and $-1.3 \text{mag}$, respectively), is presented in Figure 2. Note that the offsets of $\sim1.3 \text{mag}$, translating to a factor of $\sim3$ in flux, imply that the double-horn events can be found at a relatively wide range of flux levels of the source. Moreover, as we argue below, such a repeating pattern does not conform with the stochastic, red-noise type variability of the blazar (e.g., Rani et al. 2013; Bhatta 2016; Raiteri et al. 2021).

![Figure 1](image-url)  
Figure 1. Four monthlong TESS observations of S5 0716+714 investigated in this paper. The TESS data were converted to $R$-band magnitudes and binned in 10 minute intervals (see Section 2).

We emphasize the achromatic character of the 2014 WEBT plateau event that was clearly demonstrated by Bhatta (2016). As for the TESS data, while here we show only the TESS lightcurve converted to $R$-band magnitudes, the accompanying WEBT monitoring—even though with a more sparse coverage and not overlapping with the entirety of the TESS pointings—confirms the achromatic character of the flux changes also in the 2019/2020 data set (see Figure 3 in Raiteri et al. 2021). In particular, four out of the six events selected here for analysis have the accompanying WEBT data, which clearly show that
the flux changes traced by the dense TESS sampling, are followed closely in all the \( B, V, R, \) and \( I \) filters separately.

All in all, during the total of four months of the TESS monitoring time, we identified six potential microlensing events in the optical lightcurve of S5 0716+714. The question therefore arises on the frequency and the duty cycle of such events. In this respect, first we note that there may be more similar features in the TESS lightcurve, which are, however, more difficult to spot because of the superimposed flaring activity of the jet contaminating the magnification pattern. And indeed, due to this reason, several other possible features in the TESS data were not selected for the analysis presented below: when viewed with a sufficient zoom, they either appeared asymmetric, or the plateau during the flux minimum phase displayed some small-amplitude variability. Second, we note that whenever an intense monitoring campaign with sufficient long time coverage (of at least a handful of days) and sufficiently dense sampling (like the WEBT 2003/2014 or the TESS campaigns) had targeted the source, at least one microlensing candidate feature could be seen. On the other hand, the majority of the intranight observations of the blazar with a single ground-based telescope, lasting for several hours per night at most, are typically insufficient to cover the entirety of a single magnification event, precluding any robust identification of such.

To sum up, we conclude that the symmetric double-horn features in the optical lightcurve of S5 0716+714, with peak-to-peak duration of about 12 hr and the flux minimum phase lasting for a few/several hours, are promising microlensing-event candidates. Those events appear relatively frequent although one needs more good-quality monitoring data to estimate robustly the duty cycle and clustering properties of such.

3. Binary Lens Modeling

In the first stage of our analysis, we used the inverse-ray shooting method to obtain magnification patterns for different binary parameters. If we consider objects with masses \( M \) and \( qM \), where \( q < 1 \), at the respective positions \( x_M = [0, 0] \) and \( x_{qM} = [0, d] \) on the lens plane, the lens equation takes the form

\[
y = x - \frac{x}{|x^2|} - q \frac{x - d}{|x - d|^2},
\]

where \( y \) and \( x \) are two-dimensional angular coordinates of the rays on the source and lens planes (Schneider et al. 1992). In the above, all the quantities are in units of the Einstein angle

\[
\theta_E = \left( \frac{4GM}{c^2} \frac{D_{LS}}{D_LD_S} \right)^{1/2},
\]

where \( D_S, D_L, \) and \( D_{LS} \) are the angular distances to the source, to the lens, and between the source and the lens, respectively. Note that the Einstein radius \( R_E = \theta_E D_L \).

To obtain magnification patterns of the lens characterized by given \( q \) and \( d \) in the inverse-ray shooting method, we evenly distributed a set of rays on the lens plane and calculated the position of each ray on the source plane. For each bin of rays, the magnification is the ratio between the number of rays that ended up in it in the presence of and in the absence of the lens. In our investigation of the parameter space, we have calculated magnification patterns for various binary mass ratios from the range \( q \in [0.001, 0.5] \) and separation \( d \in [0.5, 1.5] \). We note that for small separation \( d \), magnification occurs predominantly in a compact area surrounding the center of the mass of a binary lens. If, in addition, the mass ratio is small (in practice, below 0.001), the magnification pattern resembles a point-mass lens. As the mass ratio increases, the area of magnification is also enlarged, creating various shapes whose exact appearance depends on the separation parameter. The volcano-type events with durations and magnifications resembling the ones presented in Figure 2 could be obtained for the combination \( q \lesssim 0.01 \) and \( d \approx 0.7 \).

The binary parameters, \( q \) and \( d \), determine the magnification pattern. However, in order to obtain a specific magnification
reproduced either the trajectories and compared the quality of the obtained
(curves matching a given feature present in the lightcurve, we
need four parameters defining the source trajectory (the impact
parameter between the source and the center of the mass of the
in the units of the Einstein angle, \( u_0 \); the Einstein crossing
time, \( t_E \); the time of the closest approach between the source
and the lens, \( t_0 \); and the angle between the source trajectory and
binary lens axis, \( \alpha \)), as well as the source parameter \( \rho \), which is
the radius of the source expressed as a fraction of the Einstein
radius. In the next step of the analysis, we have therefore
performed a formal fitting of those parameters to the six
selected events of the source lightcurve, utilizing the Python
package MULENSMODEL for modeling microlensing (Poleski
& Yee 2019). For magnification calculation we have chosen the
VBBL method (Bozza 2010; Bozza et al. 2018) implemented
in MULENSMODEL; fitting was performed by minimizing \( \chi^2 \),
using the algorithm described in Gao & Han (2012).

Due to a large number of parameters, it was impossible to
perform fitting with all of the model parameters allowed to vary
at the same time. For this reason, keeping in mind the general
features of the explored magnification patterns from the
inverse-ray shooting studies, in the first step of the analysis
with the MULENSMODEL, we investigated the lens parameters
by fixing \( q \) and \( d \) at different values for various source
trajectories and compared the quality of the obtained fits. It was
relatively straightforward to find in this way lenses that
reproduced either the first two (TESS19-A and TESS19-B) or
the last four (TESS20-A to TESS20-D) events; however,
finding a lens that can fit all six events for similar source
trajectories was challenging, and the best results could be
obtained for the \( q \sim 0.005 \) and \( d \sim 0.75 \) combination. To derive
the final, more precise values of the lens parameters, in the next
step of the analysis, we fit the TESS20-D event for a given
(fixed) representative source trajectory, with \( q \) and \( d \) allowed to vary
(initial values of 0.01 and 0.7, respectively), resulting in
the best-fit values of \( q = 0.00545 \) and \( d = 0.0727 \). In the final,
third step of the fitting procedure, the fit was performed for all
the selected events with the fixed lens parameters \( q = 0.00545 \)
and \( d = 0.0727 \) by thawing the source trajectory parameters \( t_E, t_0, u_0, \) and \( \alpha \). It should be noted at this point that the particular
choice of the \( \rho \) parameter does not affect the MULENSMODEL
fitting results, as long as the source appears point-like, meaning
\( \rho \ll 1 \). The final model was chosen based on the \( \chi^2 \) statistic.

As shown in Figure 3 and summarized in Table 1, the selected
events could all be fitted reasonably well in this way with only
slight changes in the source trajectory parameters \( u_0, t_E, \alpha, \)
and \( t_0 \). This is further visualized in Figure 4, where we present the
magnification map of the lens along with the source trajectory,
along with the resulting source lightcurves, corresponding to the
MULENSMODEL. The emerging set of the source trajectory (on
the lens plane) parameters is obviously not unique, and it is
possible that comparably good fits could be obtained for the
other values of \( u_0, t_E, \alpha, \) and \( t_0 \). The point of the fitting exercise
presented here is, however, to check whether the same single
binary lens is sufficient to explain all the selected events.
Moreover, we claim that this lens has to be characterized by the
parameters close to the selected values of \( q \lesssim 0.01 \) and \( d \sim 0.7 \).

4. Discussion and Conclusions

The distance to the active galaxy S5 0716+714, \( z = 0.31 \pm 0.08 \), has been determined by Nilsson et al. (2008), based on the
“standard candle” assumption for the detected host galaxy.
Danforth et al. (2013), based on the detection of the narrow
Ly\( \alpha \) forest, confirmed the 2\( \sigma \) confidence redshift range for the blazar 0.2315 < \( z \) < 0.322. More recently, Dorigo Jones et al. (2022)
found the Ly\( \alpha \) forest analysis and obtained a 95% confidence redshift range of 0.227 < \( z \) < 0.254. With such, the duration and the magnification of the TESS microlensing
events in the S5 0716+714 optical lightcurve dictate that the lens is located in close proximity to the source, \( D_{LS} \ll D_{LS} \), and in particular within the host galaxy of the blazar as otherwise,
the implied lens parameters (mass and separation) would become unrealistic. Hence, below we take \( D_{LS} \approx D_{LS} \approx d_A \).

Moreover, the lens should be located within the central parts of the host as otherwise the probability for the jet component to
cross the folded caustic would be rather low, in contrary to the
frequency of the microlensing events in the TESS lightcurve.

In general, S5 0716+714 exhibits a stochastic variability at
optical frequencies, with power spectral density (PSD) extending
as a colored-noise continuum over several decades of the
variability timescales, from months and years down to minutes (see, e.g., Rani et al. 2013; Bhatta 2016; Raiteri et al. 2021). In particular, the PSD analysis for the first season of the TESS campaign returns the best-fit power-law slope of \( \alpha = 2.01 \pm 0.04 \) (Raiteri et al. 2021), consistent with the overall red-noise behavior. In addition, however, by means of analyzing the
source periodograms, the autocorrelation function, and the
structure function, Raiteri et al. (2021) found the characteristic
variability timescales in the system of about 1.7, 0.5, and 0.2
days. It is not clear if these timescales could be linked to the
microlensing events as discussed here, especially as there are
indications that some of the rapid optical flares in the source
covered with WEBT are chromatic; yet 0.2 and 0.5 days do
seem, at least roughly, with the duration of the flux drop/
rise phases and the total duration of the analyzed microlensing-
event candidates, respectively. Hence we cautiously conclude
that the timing analysis of the TESS data do not rule out
repetitive—even in a quasiperiodical fashion—microlensing-
type structures in the red-noise lightcurve of S5 0716+714.

The overall colored-noise nature of the S5 0716+714 optical
variability indicates that the observed emission of the blazar is
produced by various emission components distributed within
an extended segment of the jet for which the scales range from
tenths and hundredths of parsecs down to the smallest scales set
by the gravitational radius of the SMBH in the galactic nucleus:

\[
\text{rg} = \frac{GM_s}{c^2} \approx \left( \frac{M_s}{10^8 M_\odot} \right) \text{au}
\]  

(see, in this context, Begelman et al. 2008). We posit that the
microlensing events (as the ones analyzed here) become conspicuous whenever the innermost segments of the jet, with
linear sizes \( R \lesssim r_g \), dominate the radiative output of the source.
A very complex kinematics of the S5 0716+714 jet—with frequent changes in the jet position angle, as well as a plethora
of radio emission features on milliarcsec scales displaying
various and often superluminal radial and nonradial motions
(e.g., Britzen et al. 2010; LarioNov et al. 2013; Rani et al. 2015)
—means that one should not hope to see any strict regularity in
such microlensing events as the source trajectory parameters
\( u_0, t_E, \) and \( \alpha \) may change/evolve with time. The encouraging
finding, in this context, is that our fitting returns a rather narrow
range for those parameters, in particular the Einstein crossing
time each time of a similar order of a few/several days.
Keeping in mind the above considerations, for the analyzed microlensing events, we therefore set the limit $R = \rho R_E > r_g$, which, combined with Equation (2) gives

$$\left( \frac{M}{10^4 M_\odot} \right) \geq \left( \frac{M_\odot}{10^8 M_\odot} \right)^2 \left( \frac{\rho}{0.01} \right)^{-2} \left( \frac{D_{LS}}{100 \text{ pc}} \right)^{-1}. \quad (4)$$

On the other hand, since by definition $R_E = c \beta_{\text{app}} / \rho$, where $\beta_{\text{app}}$ is the apparent velocity of the source emitting region through the lens, we also have

$$\left( \frac{M}{10^4 M_\odot} \right) \simeq 10^{4} \left( \frac{\beta_{\text{app}}}{30} \right)^2 \left( \frac{\rho}{2 \text{ d}} \right) \left( \frac{D_{LS}}{100 \text{ pc}} \right)^{-1}. \quad (5)$$

**Figure 3.** The MULENSMEML fits (as described in Section 3 and summarized in Table 1) to the six selected events in the TESS lightcurve of S5 0716+714 (see Figure 1).
Unfortunately, the SMBH mass in S5 0716+714 is unknown, and optical measurements of $\beta_{app}$ are not available. However, for a blazar of the BL Lac type, we expect in general $M_\ast \gtrsim 10^6M_\odot$ (Plotkin et al. 2011), and for S5 0716+714 in particular $\beta_{app} \lesssim 30$ has been measured at radio wavelengths (Rani et al. 2015). With such, setting in addition $\rho = 0.01$ and also $t_E \approx 2$ days as the average crossing time (see Table 1), the lower and upper limits are set by Equations (4) and (5), respectively and correspond to the range of the binary lens mass $10^4 < M/M_\odot < 10^8$ for the distance of the lens from the active nucleus $D_{LS} \approx 100$ pc and $10^2 < M/M_\odot < 10^4$ for $D_{LS} \approx 10$ kpc. We emphasize that the apparent velocity of the jet features inferred from radio observations with milliarcsecond resolution may not necessarily provide a proper characterization of the innermost segments of the jet dominating the optical emission subjected to the microlensing events (as proposed here). Indeed, in the framework of the established magnetohydrodynamics (MHD) model for relativistic jets launched by accreting black holes, the jet bulk velocity increases from the jet base due to a gradual collimation and acceleration of the plasma outflow by magnetic forces (e.g., Lyubarsky 2009, and references therein). Hence, apparent velocities measured in the radio domain at larger (parsec) distances from the center, $\beta_{app} \lesssim 30$ in this case, provide us a very robust upper limit for the proper motion velocity of the optical emission regions.

Another constraint on the lens could, in principle, follow from the requirement that the binary parameters should be stable during a single lensing event. However, the orbital velocity of the companion,

$$v_{orb} = \sqrt{\frac{GM}{d}} \sim 370 \left(\frac{M}{10^4 M_\odot}\right)^{1/4} \left(\frac{D_{LS}}{100 \text{ pc}}\right)^{-1/4} \text{ km s}^{-1},$$

is sufficiently low for the range of $M$ and $D_{LS}$ discussed above, that the distance traveled by the companion during the Einstein crossing time is always less than the separation of the lens. In other words, the condition $v_{orb} t_E \ll d R_E$ is easily satisfied for a wide range of lens masses located at larger distances, given the Einstein radius of the lens

$$R_E \approx 100 \left(\frac{M}{10^4 M_\odot}\right)^{1/2} \left(\frac{D_{LS}}{100 \text{ pc}}\right)^{1/2} \text{ au.}$$

On the other hand, the configuration of a binary lens could change over the 20 yr timescale (since the WEBT 2003 event), especially for the lower ranges of the mass $M$ and the source–lens distance $D_{LS} < 100$ pc. Changes in the position of the $0.00545 M_\odot$ companion on the orbit around $M$ will lead to the rotation of the magnification pattern. But a double-horn feature in the lightcurve can be obtained even for $\alpha \approx 90^\circ \pm 20^\circ$ at the expense of a slight asymmetry of the “horns” (i.e., of the magnified flux maxima). Moreover, the characteristic microlensing pattern can still be produced even with larger rotation angles by means of more substantial changes in the source trajectory parameter introduced by the precession of the jet on a similar timescale of years/decades; indeed, observational evidence for such a precession in S5 0716+714 has been discussed in, e.g., Bach et al. (2005) and Nesci et al. (2005). These two effects—namely, the orbital modulation of the lens and the jet precession, both taking place on comparable timescales, leading altogether to a systematic evolution in the magnification patterns for the lensing events—could, in fact, offer an exciting opportunity for an observational verification of the model proposed, if only the target could be monitored at optical and radio frequencies over a longer period of time with sufficiently dense coverage.

Yet another consequence of the event detected by WEBT in 2003 is that one may require the Einstein radius to be large enough to cover the blazar over a timescale of, at least, $\tau \gtrsim 20$ yr despite the host galaxy rotation. For a typical blazar with a $M_\ast \sim 10^6 M_\odot$ black hole, the velocity dispersion of the host is expected to be around $\sigma_{vel} \approx 200$ km s$^{-1}$. With such, assuming the lens is beyond the central SMBH sphere of influence (central $\sim 10$ pc region), the condition $\sigma_{vel} \tau < R_E$ gives

$$\left\{ \frac{M}{10^4 M_\odot} \right\} > 10^2 \left[ \frac{\sigma_{vel}}{200 \text{ km s}^{-1}} \right]^2 \times \left( \frac{\tau}{20 \text{ yr}} \right)^2 \left(\frac{D_{LS}}{100 \text{ pc}}\right)^{-1},$$

Table 1

| Parameter      | TESS19-A | TESS19-B | TESS20-A | TESS20-B | TESS20-C | TESS20-D |
|----------------|----------|----------|----------|----------|----------|----------|
| $\rho$         | 0.013$^f$| 0.013$^f$| 0.013$^f$| 0.013$^f$| 0.013$^f$| 0.013$^f$|
| $q$            | 0.00545$^f$| 0.00545$^f$| 0.00545$^f$| 0.00545$^f$| 0.00545$^f$| 0.00545$^f$|
| $d$            | 0.727$^f$| 0.727$^f$| 0.727$^f$| 0.727$^f$| 0.727$^f$| 0.727$^f$|
| $u_0$          | 0.36     | 0.35     | 0.48     | 0.78     | 0.75     | 0.54     |
| $t_E$          | 3.0      | 4.0      | 3.4      | 2.4      | 1.5      | 1.7      |
| $\alpha$       | 89       | 94       | 82       | 88       | 87       | 94       |
| $\ell_0$ [BTJD] | 1843.78  | 1845.92  | 1849.62  | 1852.30  | 2026.66  | 2030.00  |
| $\ell_0$ [UTC] | 2019-12-26| 2019-12-28| 2020-01-01| 2020-01-03| 2020-06-26| 2020-06-29|
| $\chi^2$/dof   | 1.91     | 1.5      | 3.75     | 2.10     | 0.93     | 0.89     |

Note.
$^f$ parameter frozen in the fitting procedure.
which provides the strongest lower limit on the mass of the lens. In particular, the above Equation (8), together with the upper limit following from Equation (5), yield $10^6 < M/M_\odot < 10^8$ for the distance $D_{LS} \simeq 100$ pc and $10^4 < M/M_\odot < 10^6$ for $D_{LS} \simeq 10$ kpc.

All in all, our analysis of the optical lightcurves of S5\,0716+714 resulting from the TESS observations is consistent with the presence of a massive binary lens containing an IMBH, possibly even a supermassive one, and a much less massive companion (by a factor of $\leq 0.01$), located within the host galaxy of the blazar (most likely the central kpc regions).

Until now, no robust detections of any radiative or dynamical signatures for the presence of IMBHs have been reported although several models and scenarios are being discussed in the literature identifying IMBHs with ultraluminous X-ray sources, centers of dwarf galaxies, or centers of globular clusters (for reviews, see Mezcua 2017; Greene et al. 2020). Interestingly, gravitational lensing of background stars by globular clusters in our galaxy has been proposed as a viable method for detecting such IMBHs (Kains et al. 2016, 2018). Globular clusters are, moreover, expected to be more numerous in massive ellipticals than in galaxies such as our Milky Way (Harris et al. 2017; Lim et al. 2020).

We also note in this context recent N-body simulations of globular clusters, which not only reveal the presence of IMBHs but also the fact that most of such IMBHs are in binary systems (see, e.g., Konstantinidis et al. 2013; Leigh et al. 2013). According to our modeling, the IMBH lens in the host galaxy of S5\,0716+714 should be accompanied by a much less massive (ratio 1:200) object. This mass ratio is within the range of the intermediate mass-ratio inspirals, mergers of which can be probed in the near future directly with the Laser Interferometer Space Antenna gravitational-wave detector (see the recent review by Amaro-Seoane et al. 2022), with the conservative estimate of the detection rate of about two per year for the events at high redshifts (Pestoni et al. 2021).

Currently, the only observational clue we have regarding the population of binary black holes approaching the IMBH range is a large number of black hole binaries discovered by the Advanced LIGO and Advanced Virgo gravitational-wave detectors, with the merger rate density estimated at $23.9_{-8.6}^{+14.9}$ Gpc$^{-3}$ yr$^{-1}$ (Abbott et al. 2021), albeit in a lower-mass range of 14–150 $M_\odot$. Until now, no signal for merging of more massive systems has been found in the LIGO/Virgo data (Abbott et al. 2022), and the estimated rate of mergers for binaries with the total masses of $150M_\odot$ is $\sim 0.08$ Gpc$^{-3}$ yr$^{-1}$.

We propose that lensing events of the sort we advocate for S5\,0716+714 are in fact not uncommon among blazars, but the actual number of lensed sources and lensing events in a single source could be estimated only with a systematic optical monitoring of a larger number of targets with a sufficiently dense sampling. The underlying red noise-type intrinsic variability of blazar jets is the other major obstacle in a robust identification of microlensing events; finding a proper statistical test in this context is not straightforward and relates to a wider open problem of assigning a significance to recurring features in the periodograms of colored-noise time series. The events we have selected in the TESS lightcurve of S5\,0716+714 are all very regular, symmetric in shape, and in addition, of a comparable duration. Moreover, the events are found during different flux levels of the source. While these improve our confidence in the lensing hypothesis, we caution the reader that the precise physical mechanisms that lead to intrinsic blazar optical variability have not yet been identified, which makes it difficult to conclusively establish lensing as the cause of the symmetric variations with the available data.

Lastly, we emphasize again an important aspect of the proposed scenario, namely, that we do expect the proposed lensing events in the optical lightcurve of S5\,0716+714 to repeat, even though not necessarily in a periodic or even quasiperiodic fashion. Moreover, the orbital modulation of the lens expected to take place on the timescale of years/decades for the lens–source distances $< 100$ pc and large lens masses $M > 10^5M_\odot$ offers an exciting possibility for observational tests of the model by detecting a systematic evolution in the magnification patterns for the lensing events (modulo systematic changes in the jet trajectory parameters due to the jet precession).
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ORCID iDs
D. Ł. Król @ https://orcid.org/0000-0002-3626-5831
Ł. Stawarz @ https://orcid.org/0000-0001-8294-9479
J. Krzesinski @ https://orcid.org/0000-0001-8320-3919
C. C. Cheung @ https://orcid.org/0000-0002-4377-0174

References
Abbott, R., Abbott, T. D., Abraham, S., et al. 2021, PhRvX, 11, 021053
Abbott, R., Abbott, T. D., Acernese, F., et al. 2022, A&A, 659, A84
Amaro-Seoane, P., Andrews, J., Arca Sedda, M., et al. 2022, arXiv:2203.06016
Begelman, M. C., Fabian, A. C., & Rees, M. J. 2008, MNRAS, 384, L19
Bhatta, G., Stawarz, Ł., Ostrowski, M., et al. 2016, ApJ, 831, 92
Bach, U., Krichbaum, T. P., Ros, E., et al. 2005, A&A, 433, 815
Blandford, R. D., & Narayan, R. 1992, ARA&A, 30, 311
Bozza, V., Bachelet, E., Bartolici, F., et al. 2018, MNRAS, 479, 5157
Britzen, S., Kudryavtseva, N. A., Witzel, A., et al. 2010, A&A, 511, A57
Danforth, C. W., Nalewajko, K., France, K., et al. 2013, ApJ, 764, 57
Dorigo Jones, J., Johnson, S. D., Muzahid, S., et al. 2022, MNRAS, 509, 4330
Gao, F., & Han, L. 2012, Comput. Optimi.-Appl., 51, 259
Greene, J. E., Strader, J., & Ho, L. C. 2020, ARA&A, 58, 257
Harris, W. E., Cicone, S. M., Eadie, G. M., et al. 2017, ApJ, 835, 101
Kains, N., Bramich, D. M., Sahu, K. C., & Calamida, A. 2016, MNRAS, 460, 2025
Kains, N., Calamida, A., Sahu, K. C., et al. 2018, ApJ, 867, 37
Konstantinidis, S., Amaro-Seoane, P., & Kokkotas, K. D. 2013, A&A, 557, A135
Larionov, V. M., Jorstad, S. G., Marscher, A. P., et al. 2013, ApJ, 768, 40
Leigh, N. W. C., Boker, T., Maccarone, T. J., & Perets, H. B. 2013, MNRAS, 429, 2997
Lim, J., Wong, E., Ohyama, Y., Broadhurst, T., & Medezinski, E. 2020, NatAs, 4, 153
Lyubarsky, Y. 2009, ApJ, 698, 1570
Mao, S., & Paczynski, B. 1991, ApJL, 374, 157
Mezcua, M. 2017, IJMPD, 26, 1730021
Narayan, R., & Bartelmann, M. 1996, arXiv:astro-ph/9606001
Nesci, R., Massaro, E., Rossi, C., et al. 2005, AJ, 130, 1466
Nilsson, K., Pursimo, T., Sillanpää, A., et al. 2008, A&A, 487, L29
Ostorero, L., Wagner, S. J., Gracia, J., et al. 2006, A&A, 451, 797
Peirson, A. L., Liodakis, I., Readhead, A. C. S., et al. 2022, ApJ, 927, 24
Pestoni, B., Bortolas, E., Capelo, P. R., & Mayer, L. 2021, MNRAS, 500, 4628
Plotkin, R. M., Markoff, S., Trager, S. C., & Anderson, S. F. 2011, MNRAS, 413, 805
Poleski, R., & Yee, J. C. 2019, A&C, 26, 35
Raiteri, C. M., Villata, M., Carosati, D., et al. 2021, MNRAS, 501, 1100
Rani, B., Krichbaum, T. P., Fuhrmann, L., et al. 2013, A&A, 552, A11
Rani, B., Krichbaum, T. P., Marscher, A. P., et al. 2015, A&A, 578, A123
Ricker, G. R., Winn, J. N., Vanderspek, R., et al. 2015, JATIS, 1, 014003
Schneider, P., Ehlers, J., & Falco, E. E. 1992, Gravitational Lenses XIV. Also Astronomy and Astrophysics Library (Berlin: Springer), 112
Schneider, P., & Weiss, A. 1987, A&A, 171, 49
Schneider, P., & Weiss, A. 1986, A&A, 164, 237
Subramanian, K., Chitre, S. M., & Narasimha, D. 1985, ApJ, 289, 37
Vedantham, H. K., Readhead, A. C. S., Hovatta, T., et al. 2017, A&AS, 453, 89
Wambsganss, J. 2006, in Saas-Fee Advanced Course 33, Gravitational Lensing: Strong, Weak and Micro, ed. G. Meylan, P. Jetzer, & P. North (Berlin: Springer), 453