Detection of minute-timescale $\gamma$-ray variability in BL Lacertae by Fermi-LAT

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ABSTRACT

BL Lacertae, the prototype of the BL Lacertae (BL Lac) category of blazars, underwent a giant $\gamma$-ray flare in April 2021. The Large Area Telescope (LAT) onboard the Fermi Gamma-ray Space Telescope (hereafter Fermi-LAT) observed a peak $\gamma$-ray ($0.1-500\text{ GeV}$) flux of $\sim 2 \times 10^{-7} \text{ photons cm}^{-2} \text{ s}^{-1}$ within a single orbit on 2021 April 27, which is historically the brightest $\gamma$-ray flux ever detected from the source. Here, we report, for the first time, the detection of significant minute-timescale GeV $\gamma$-ray flux variability in the BL Lac subclass of blazars by the Fermi-LAT. We resolved the source variability down to 2-min binned timescales with a flux halving time of $\sim 1$ minute, which is the shortest GeV variability timescale ever observed from blazars. The detected variability timescale is much shorter than the light-crossing time ($\sim 14$ minutes) across the central black hole of BL Lac indicating a very compact $\gamma$-ray emission site within the outflowing jet. Such a compact emitting region requires the bulk Lorentz factor of the jet to be larger than 16 so that the jet power is not super Eddington. We found a minimum Doppler factor $\delta_{\text{min}}$ of 15 using the $\delta$ function approximation for the $\gamma\gamma$ opacity constraint. For a conical jet geometry, considering $\Gamma = \delta_{\text{min}}$, the observed short variability timescale suggests the very compact emission region to lie at a distance of about $6.2 \times 10^{17}$ cm from the central engine of BL Lac.

Key words. galaxies: active – BL Lacertae objects: general – BL Lacertae objects: individual (BL Lac)

1. Introduction

The extragalactic $\gamma$-ray sky is dominated by the blazar category of active galactic nuclei (AGN; Abdollahi et al. 2020). Blazars comprising flat-spectrum radio quasars (FSRQs) and BL Lac objects (BL Lacs) are radio-loud AGN that have their relativistic jets aligned close to the line of sight to the observer (Blandford & Rees 1978; Urry & Padovani 1995). They emit most of their energy in high energy $\gamma$-rays with the most powerful sources, during strong flares reaching $\gamma$-ray luminosities in the isotropic emission scenario as high as $L_{\gamma} \sim 10^{48}$–$10^{49}$ erg s$^{-1}$ (Aharonian et al. 2017). The broadband spectral energy distributions (SEDs) of blazars have double-hump structures (Fossati et al. 1998). The low-energy component of the SED is well explained by synchrotron emission from the relativistic electrons within the jet, while the origin of the high-energy component is still unclear (e.g. Böttcher 2007). One among the mechanisms responsible for the high energy $\gamma$-ray radiation is the synchrotron self Compton (SSC) process by which the synchrotron photons emitted by the relativistic electrons in the jet are Compton up-scattered by the same population of electrons in the jet (Maraschi et al. 1992). The other model posits the production of $\gamma$-rays by inverse Compton scattering of seed photons external to the jet, by electrons in the emitting jet. The seed photons could be the ultraviolet photons from the accretion disk (Dermer & Schlickeiser 1993), the photons from emission lines from the broad-line region (Sikora et al. 1993) and the infrared emission from the dusty torus (Blazejowski et al. 2000). Alternatively, hadronic processes could also produce $\gamma$-rays (Böttcher et al. 2013). Based on the synchrotron peak frequency ($\nu_{\text{peak}}$) of their SEDs, BL Lacs are further divided into low-frequency peaked BL Lacs (LBLs; $\nu_{\text{peak}} \leq 10^{14}$ Hz), intermediate-frequency peaked BL Lacs (IBLs; $10^{14}$ Hz $< \nu_{\text{peak}} < 10^{15}$ Hz), and high-frequency peaked BL Lacs (HBLs; $\nu_{\text{peak}} \geq 10^{15}$ Hz) (Padovani & Giommi 1995; Abdo et al. 2010a).

The $\gamma$-rays from blazars are known to be highly variable (Abdo et al. 2010b; Rajput et al. 2020) which indicates the emission region is highly compact (Fichtel et al. 1994), and the $\gamma$-ray radiation is highly beamed (Dondi & Ghisellini 1995). However, the exact physical processes that are responsible for the generation of the observed $\gamma$-ray emission, as well as their production site, are uncertain and highly debated. Using powerful observational facilities in the $\gamma$-ray domain, rapid $\gamma$-ray variations have been detected in seven AGN so far, including three BL Lacs (PKS 2155-304 (Aharonian et al. 2007), Mrk 501 (Albert et al. 2007), BL Lac (Arlen et al. 2013; MAGIC Collaboration et al. 2019)), three FSRQs (PKS 1222+21 (Aleksic et al. 2011), 3C 279 (Ackermann et al. 2016), CTA 102 (Ackermann et al. 2016), and one radio galaxy (IC 310 (Aleksic et al. 2014). However, the minute-timescale $\gamma$-ray variations were also detected multiple times in the same source. For example, Arlen et al. (2013) observed a rapid TeV $\gamma$-ray flare from BL Lac with an exponential decay time of 13±4 min and recently, MAGIC Collaboration et al. (2019) also reported the detection of VHE $\gamma$-ray flare with halving time of 26±8 min from the same source. Moreover, the majority of the findings of rapid $\gamma$-ray variations come from VHE observations by the ground-based Cerenkov telescopes except for two sources, namely 3C 279 (Ackermann et al. 2016) and CTA 102 (Shukla et al. 2018), where the short time scale variations are from the GeV observations by the Fermi-LAT. Both of these sources belong to the FSRQ subclass of blazars. To date, no rapid GeV $\gamma$-ray variability was detected in any BL Lacs by the Fermi-LAT. The
availability of data from the Fermi-LAT (Atwood et al. 2009) observations provide ample opportunities to find evidence of short time scale of variations in more blazars. Our motivation here is to find rapid γ-ray variations in the BL Lac subclass of blazars using the Fermi-LAT observations. BL Lac, at a redshift of z=0.069 (Miller et al. 1978), is an eponym of the BL Lac category of blazars. It is usually categorized as an LBL (Nilsson et al. 2018), but sometimes it is also classified as an IBL (Ackermann et al. 2011). During April 2021, the Fermi-LAT observed the historically largest γ-ray flare from BL Lac, which allowed us to search for the rapid γ-ray variations in the source. In this work, we report the first-ever detection of minute-timescale γ-ray variability in any BL Lac object by Fermi-LAT.

This paper is organized as follows. In Section 2 we give an overview of observations and the data analysis of Fermi-LAT. Results of our rapid γ-ray variability study are given in the Section 3. Section 4 presents the discussion and the summary of our work is given in the Section 5.

2. Observations and Data Analysis

2.1. Gamma-ray observations

We used the Pass 8 (P8R3) Fermi-LAT γ-ray (0.1–500 GeV) data of BL Lac from MJD 59305 (2021 April 1) to MJD 59340.
(2021 May 6). We analyzed the data following the standard LAT data analysis procedure\(^1\) and using the Fermi Tool software package version 2.0.8 with the P8R3_SOURCE_V3 instrument response functions. For our analysis, we chose all the SOURCE class events (evclass=128 and evtype=3) within a circular region of 10 degrees (region of interest; ROI) around the blazar BL Lac. To select the good time intervals, we used a filter \(\text{"(DATA\\_QUAL>0)\&\&(LAT\\_CONFIG==1)"}\) and applied a maximum zenith-angle cut of 90 degrees to avoid the background \(\gamma\)-rays from the Earth’s limb. We employed the unbinned maximum likelihood optimization technique for flux determination and spectral modelling\(^2\) during the initial likelihood fit, all the parameters of the sources lying outside the ROI were kept fixed to their values in 4FGL, while the normalization and the spectral parameters of the sources within the ROI were left to vary freely. The normalizations of the diffuse emission components were also left free.

### 2.2. X-ray observations

We generated the X-ray spectrum of BL Lac using the online Swift-XRT data products generator tool\(^3\)\(^,\)\(^4\) (for details, see Evans et al.\(^5\), 2009). This tool produces the pile-up corrected source spectrum, the background spectrum and the response files using the HEASOFT version 6.29. The X-ray spectrum of BL Lac was fitted with an absorbed power-law model in the XSPEC version 12.12.0 to obtain the 0.3–10 keV X-ray flux and the photon index. For the fitting, we assumed a fixed Galactic hydrogen column density of \(n_H = 3.03 \times 10^{21} \text{cm}^{-2}\) (Willingale et al.\(^6\), 2013).

### 3. Results

#### 3.1. \(\gamma\)-ray light curve

Figure 1 presents the \(\gamma\)-ray light curves of BL Lac for a period of about one month that includes the brightest outburst observed on 2021 April 27. Although the spectral shape of BL Lac is defined as log-parabola (LP) in the 4FGL catalog\(^7\) (Abdollahi et al.\(^8\), 2020), we generated the light curves by modeling the spectra in each time bin as a simple power-law (PL), since the PL indices have smaller statistical uncertainties than those obtained from the complex LP model (e.g. Abdo et al.\(^9\), 2011). Also, choosing a simple PL model is more appropriate for this work as we are probing the shortest timescale \(\gamma\)-ray variations, thereby dealing with lesser photon statistics. The arrival time and the energy of the highest energy photon (bottom panel) coming from the source were derived using the tool gtscapro on ULTRA-CLEAN event class (evclass=512).

The maximum 1-day averaged flux (above 100 MeV) was observed on MJD 59331\(^{(3)}\) (2021 April 27) reaching \(6.8 \pm 0.3 \times 10^{-6} \text{photons cm}^{-2} \text{s}^{-1}\), which is the highest daily binned flux ever observed from this source. The photon index corresponding to this highest flux is 1.90 \pm 0.03, which is slightly harder than the value \(2.025\) mentioned in the 4FGL catalog. The 3-hr binned \(\gamma\)-ray light curve of BL Lac, shown in panel (c) of Figure 1\(^{(2)}\) indicates two sharp \(\gamma\)-ray flares.

To investigate any instrumental uncertainties in the analysis, we also generated the daily-binned light curves of BL Lac in 0.1-1 GeV, 1-50 GeV, and 50-500 GeV energy bands for the period considered. As seen in Figure 2, the light curves in those three energy bands follow a pattern similar to the total 0.1-500 GeV energy band light curve. There are only six data points in the 50-500 GeV light curve as the source was not significantly detected in this energy range in other time bins.

The highest-energy photon, 128 GeV, was recorded with >99.99% probability on MJD 59333 (2021 April 29), which is at the decline phase of the main flare. A similar trend was also seen in 3C 279 where the highest energy photon was observed at the end of the outburst phase (Ackermann et al.\(^{10}\), 2016).

#### 3.2. Sub-orbital timescale variability

As shown in panel (c) of Figure 1 the source flux exceeded the value of \(10^{-5} \text{photons cm}^{-2} \text{s}^{-1}\) on two days namely, 2021 April 23 (MJD 59327) and 2021 April 27 (MJD 59331) on three occasions with high photon statistics; MJD 59327.18756 (\(T_s = 798.985\)), MJD 59331.18756 (\(T_s = 1968.951\)), and MJD 59331.31256 (\(T_s = 776.058\)). This allowed us to further resolve the light curve with shorter timescales on these two days. We

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1. [https://fermi.gsfc.nasa.gov/ssc/data/analysis/](https://fermi.gsfc.nasa.gov/ssc/data/analysis/)
2. [gll_iem_v07](https://fermi.gsfc.nasa.gov/ssc/data/analysis/)
3. [iso_P8R3_SOURCE_V3_v1](https://heasarc.gsfc.nasa.gov/docs/heasoft/toolkit/lcviewer.html)
4. [https://www.swift.ac.uk/user_objects/](https://www.swift.ac.uk/user_objects/)
first generated the light curves with bin size equal to the orbital period (~95.4 minutes) of the Fermi–LAT. The orbit-binned light curves of BL Lac on 2021 April 23 (left) and April 27 (right) are shown in the top panels of Figure 3. We estimated the shortest flux doubling/halving timescales on these two epochs as follows:

\[ F(t_2) = F(t_1) \times 2^{\Delta t/\tau} \]  

(1)

Here, \( F(t_1) \) and \( F(t_2) \) are the flux values at times \( t_1 \) and \( t_2 \) respectively. \( \Delta t = t_2 - t_1 \) and \( \tau \) denotes the flux doubling/halving timescale. We observed a flux halving timescale of \( \sim 4\sigma \) during the decay of the flare on MJD 59327. We also detected a flux doubling timescale of \( \sim 1.14\sigma \) with \( \sim 6\sigma \) significance during the rise on MJD 59331.

To understand the temporal evolution of the flux, we fitted the peaks of orbit-binned light curves by a function of the sum of exponential defined as \( \text{(Abdo et al. 2010b)} \)

\[ F(t) = 2F_0\left( e^{\frac{-t}{\tau_1}} + e^{\frac{-t}{\tau_2}} \right)^{-1} \]  

(2)

Here, \( F_0 \) is the flux value at time \( t_0 \), denoting the flare amplitude, \( T_r \) is the rise time, and \( T_d \) is the decay time of the flare. The results of the fit are given in Table 1. We also estimated a parameter \( \xi = (T_d - T_r)/(T_r + T_d) \) that describes the symmetry of the flares \( \text{(Abdo et al. 2010b)} \). For both the flares, we found \( -0.3 < \xi < 0.3 \), implying that these flares are symmetric.

Rapid flux variations with high photon statistics observed on MJD 59327 and MJD 59331 provide us with an opportunity to examine ultra-fast flux variations on the timescale of a few minutes. To detect such rapid flux variations, we generated 2-min, 3-min and 5-min binned light curves for each orbit on these two days. Similar to \( \text{Ackermann et al. (2016)} \) and \( \text{Shukla et al. (2018)} \), we searched for minute-scale variability on these two days by fitting a constant flux to each orbit for all three time bins and subsequently, computing the probability (\( p \)-values) of the flux to be constant. Since the detection of minute-timescale \( \gamma \)-ray variations are very rare, we conservatively chose 95\% confidence level (\( p \)-value smaller than 0.05) as the detection limit for sub-orbital variability. On MJD 59327, the \( p \)-values for all the orbits and for all the time bins are found to be consistent with constant flux. Similarly, on MJD 59331, for all the orbits, except orbit E, we obtained \( p \)-values denoting no flux variations for all the time bins. For orbit E, we detected minute-scale variability in the 2-min binned (\( p=0.0065, \chi^2/dof = 27.52/12 \)) and 5-min binned (\( p=0.0202, \chi^2/dof = 13.36/5 \)) light curves. However, in the 3-min binned light curve of orbit E the variations were not significant (\( p=0.6339, \chi^2/dof = 6.12/8 \)). Our \( p \)-values are comparable to those found by \( \text{Ackermann et al. (2016)} \) in a single orbit, during a giant flare of blazar 3C 279. The 2-min binned and 5-min binned light curves for orbit E are shown in the top panels in Figure 4. We also searched for the flux doubling/halving timescales in these light curves using Equation 1. We found a halving time scale of \( \sim (1 \pm 0.3) \) minute with \( \sim 3.2\sigma \) in the 2-min binned light curve of orbit E.

### 3.3. Gamma-ray spectral variability

We investigated the \( \gamma \)-ray spectral variability of BL Lac on different time bins, namely, daily, orbital and shortest time bins. For all the time bins, the average PL photon indices are somewhat harder than its value (2.2025) in the 4FGL catalog. The average PL photon indices for these time bins are given in Table 2. We also searched for any correlation between the observed \( \gamma \)-ray flux and the PL index on these time bins using the Pearson correlation. The results of the correlation study are given in Table 3. As seen from Table 2, no significant correlation was found between the \( \gamma \)-ray flux and PL index on any of the time bins except on the 2-min time bin. We found a significant (\( p < 0.01 \)) positive correlation between \( \gamma \)-ray flux and PL index in the 2-min binned light curve indicating a softer-when-brighter trend. The variation of PL photon index with \( \gamma \)-ray flux for 2-min binned light curve of orbit E is shown in Figure 5.
Table 2. Results of spectral variability of BL Lac on different time bins. Here, \( r \) and \( p \) represent the Pearson correlation coefficient and the null hypothesis probability, respectively.

| Bin size       | Average PL index | Flux vs PL index |
|---------------|------------------|-----------------|
| 1-day         | 1.95±0.02        | -0.16           | 0.349 |
| 1-Orbit (flare 1) | 2.11±0.08        | -0.38           | 0.161 |
| 1-Orbit (flare 2) | 1.93±0.04        | -0.14           | 0.622 |
| 2-min (orbit E) | 2.02±0.11        | 0.76            | 0.003 |
| 5-min (orbit E) | 2.06±0.14        | 0.59            | 0.209 |

Fig. 5. Variation of PL photon index with \( \gamma \)-ray flux for the 2-min binned light curve of orbit E. A softer-when-brighter trend is clearly visible.

4. Discussion

For the first time, a rapid (minute-timescale) \( \gamma \)-ray variability is detected in any BL Lac category of blazars by Fermi-LAT. We observed significant variations in the minute-scale binned \( \gamma \)-ray light curves with a halving timescale of \( \sim 1 \) minute during the historically bright \( \gamma \)-ray flare from BL Lac on MJD 59331. The detection of such a rapid variability timescale challenges the existing \( \gamma \)-ray emission models.

The black hole mass for BL Lac is \( 1.7 \times 10^8 \) M\(_{\odot}\) (Zamannasab et al. 2014) and the corresponding event horizon light-crossing time is \( \sim 14 \) minutes. The detected variability timescale (\( \sim 1 \) minute) is much shorter than the event horizon light-crossing time indicating that the enhanced \( \gamma \)-ray emission is coming from a very compact region within the jet. Such rapid variations could be triggered either by dissipation in a small fraction of the black hole magnetosphere at the base of the jet or by small scale instabilities within the jet (Begelman et al. 2008). Alternatively, the jet could be much more extended and the emission can come from a localized region in the jet much smaller than the width of the jet itself. In this scenario too, the innermost region of the jet at the sub-parsec level is responsible for the observed GeV emission.

The total jet power that is required to produce the observed \( \gamma \)-ray luminosity \( L_\gamma \sim 5 \times 10^{47} \) erg s\(^{-1}\) is \( L_j = L_\gamma/(\eta_l \Gamma^2) \), where \( \eta_l \sim 0.1 \) is the radiative jet efficiency (Ackermann et al. 2016). The jet power should be less than the Eddington luminosity \( L_{\text{Edd}} \sim 2 \times 10^{46} \) erg s\(^{-1}\) which implies that \( \Gamma > 16 \).

The minimum Doppler factor, \( \delta_{\text{min}} \), of the \( \gamma \)-ray emission region can also be estimated numerically using a \( \delta \)-function approximation for the \( \gamma \gamma \) opacity constraint and the detected high energy \( \gamma \)-ray photons (Dondi & Ghisellini 1995; Ackermann et al. 2010). Assuming that the \( \gamma \)-rays are produced via the SSC scattering process and the target photons for SSC are X-ray photons, a lower limit of the Doppler factor can be calculated as

\[
\delta_{\text{min}} = \frac{\sigma_T d_l(1+z)^2 f_E E_1^{1/6}}{4\pi m_e c^4} \tag{3}
\]

where \( \sigma_T \) is the Thomson scattering cross section, \( d_l = 307 \) Mpc is the luminosity distance, \( f_E = 7 \times 10^{-11} \) erg cm\(^{-2}\) s\(^{-1}\) is the X-ray flux obtained from the Swift-XRT observation (obsid 00034748061; X-ray photon index = 2.28±0.08), and \( E_1 = 26 \) GeV/m\(_e^2\) is the highest energy photon. We estimated \( \delta_{\text{min}} \) to be \( \sim 15 \), which is consistent with the \( \delta_{\text{min}} \) = 13-17 obtained by Arlen et al. (2013).

Flares seen on the orbit-binned light curves have a symmetric profile and can thus be associated with the crossing time of radiation through the emitting region or can be explained by the superposition of several short-duration flares (Abdo et al. 2010b).

5. Summary

In this work, we report the first detection of minute-timescale GeV \( \gamma \)-ray variability in the BL Lac category of blazars by Fermi-LAT. We detected a flux halving timescale of \( \sim 1 \) minute from BL Lac on 2021 April 27. This observed short timescale of variability requires a minimum bulk Lorentz factor of 16 to have the jet power lesser than the Eddington value. Also, \( \gamma \gamma \) transparency argument for that epoch of short timescale variability detection requires a minimum Doppler factor of \( \sim 15 \). We found a softer-when-brighter trend in the 2-min binned light curve of orbit E.

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References

Abdo, A. A., Ackermann, M., Aguado, I., et al. 2010a, ApJ, 716, 30
Abdo, A. A., Ackermann, M., Ajello, M., et al. 2011, The Astrophysical Journal, 733, L26
Abdo, A. A., Ackermann, M., Ajello, M., et al. 2010b, ApJ, 722, 520
Abdo, A. A., Ackermann, M., Ajello, M., et al. 2009, ApJS, 183, 46
Abdollahi, S., Acero, F., Ackermann, M., et al. 2020, ApJS, 247, 33
Ackermann, M., Ajello, M., Allafort, A., et al. 2011, ApJ, 734, 171
Ackermann, M., Anantua, R., Asano, K., et al. 2016, ApJ, 824, L20
Ackermann, M., Asano, K., Atwood, W. B., et al. 2010, ApJ, 716, 1178
Aharonian, F., Akhperjanian, A. G., Bazer-Bachi, A. R., et al. 2007, ApJ, 664, L71

Assuming \( H_0 = 71 \) km s\(^{-1}\) Mpc, \( \Omega_M = 0.27 \), \( \Omega_\Lambda = 0.73 \) (Larson et al. 2011).
Aharonian, F. A., Barkov, M. V., & Khangulyan, D. 2017, ApJ, 841, 61
Albert, J., Aliu, E., Anderhub, H., et al. 2007, ApJ, 669, 862
Aleksić, J., Ansoldi, S., Antonelli, L. A., et al. 2014, Science, 346, 1080
Aleksić, J., Antonelli, L. A., Antoranz, P., et al. 2011, ApJ, 730, L8
Arlen, T., Aune, T., Beilicke, M., et al. 2013, ApJ, 762, 92
Atwood, W. B., Abdo, A. A., Ackermann, M., et al. 2009, ApJ, 697, 1071
Bagelman, M. C., Fabian, A. C., & Rees, M. J. 2008, MNRAS, 384, L19
Blandford, R. D. & Rees, M. J. 1978, in BL Lac Objects, ed. A. M. Wolfe, 328–341
Błazejowski, M., Sikora, M., Moderski, R., & Madejski, G. M. 2000, ApJ, 545, 107
Böttcher, M. 2007, Ap&SS, 307, 69
Böttcher, M., Reimer, A., Sweeney, K., & Prakash, A. 2013, ApJ, 768, 54
Dermer, C. D. & Schlickeiser, R. 1993, ApJ, 416, 458
Dondi, L. & Ghisellini, G. 1995, MNRAS, 273, 583
Dondi, L. & Ghisellini, G. 1995, Monthly Notices of the Royal Astronomical Society, 273, 583
Evans, P. A., Beardmore, A. P., Page, K. L., et al. 2009, MNRAS, 397, 1177
Fichtel, C. E., Bertsch, D. L., Chiang, J., et al. 1994, ApJS, 94, 551
Fossati, G., Maraschi, L., Celotti, A., Comastri, A., & Ghisellini, G. 1998, MNRAS, 299, 433
Larson, D., Dunkley, J., Hinshaw, G., et al. 2011, ApJS, 192, 16
MAGIC Collaboration, Acciari, V. A., Ansoldi, S., et al. 2019, A&A, 623, A175
Maraschi, L., Ghisellini, G., & Celotti, A. 1992, ApJ, 397, L5
Miller, J. S., French, H. B., & Hawley, S. A. 1978, ApJ, 219, L85
Nilsson, K., Lindfors, E., Takalo, L. O., et al. 2018, A&A, 620, A185
Padovani, P. & Giommi, P. 1995, ApJ, 444, 567
Rajput, B., Stalin, C. S., & Rakshit, S. 2020, A&A, 634, A80
Shukla, A., Mannheim, K., Patel, S. R., et al. 2018, ApJ, 854, L26
Sikora, M., Begelman, M. C., & Rees, M. J. 1994, ApJ, 421, 153
Urry, C. M. & Padovani, P. 1995, PASP, 107, 803
Willingale, R., Starling, R. L. C., Beardmore, A. P., Tanvir, N. R., & O’Brien, P. T. 2013, MNRAS, 431, 394
Zamaninasab, M., Clausen-Brown, E., Savolainen, T., & Tchekhovskoy, A. 2014, Nature, 510, 126

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