Fermi-LAT Detection of a Transient γ-Ray Source in the Direction of a Distant Blazar B3 1428+422 at z = 4.72

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Abstract

We report the detection of a transient γ-ray source in the direction of B3 1428+422 (z = 4.72) by analyzing the 110-month Fermi-LAT Pass 8 data. The new transient γ-ray source is far away from the Galactic plane and has a rather soft spectrum, in agreement with being a high redshift blazar. We suggest that the newly discovered transient is the γ-ray counterpart of B3 1428+422, which could be the most distant GeV source detected so far. The detection of a group of such distant γ-ray blazars will be helpful in reconstructing the evolution of the luminosity function and studying the extragalactic background light at such high redshifts.

Key words: galaxies: active — galaxies: high-redshift — galaxies: jets — gamma-rays: galaxies — quasars: individual (B3 1428+422)

1. Introduction

Blazars, including flat-spectrum radio quasars (FSRQs) and BL Lacertae objects (BL Lacs), are an extreme subclass of active galactic nuclei (AGNs) whose strong relativistic jets are closely aligned with our line of sight (Blandford & Rees 1978; Urry & Padovani 1995). Because the jet emissions are strongly boosted due to relativistic effects, they are the dominant population among the extragalactic γ-ray sky (e.g., Acero et al. 2015). At early cosmic time, blazars served as luminous beacons (e.g., Romani et al. 2004), harboring supermassive black holes (SMBHs) heavier than one billion solar masses (Ghisellini et al. 2010). High-redshift blazars not only provide crucial information of formation and growth of the first generation of SMBHs as well as their jets, but also reveal the potential impacts of the jets on the evolution of AGNs along with their host galaxies (e.g., Volonteri 2010; Fabian 2012).

Some quasars tentatively classified as blazars with redshifts of z ≥ 5 have been discovered (Romani et al. 2004; Sbarra et al. 2012; Ghisellini et al. 2014; Yi et al. 2014). However, none of these sources have been identified as γ-ray emitters. NVSS J151002+570243 (z = 4.3, Flesch 2015) is the most distant γ-ray blazar reported in the literature (Ackermann et al. 2017). One of the major characteristics of these high-redshift sources is that they have softer γ-ray spectra (Γγ ≃ 3, Ackermann et al. 2017; Li et al. 2018) than the nearby sources (Γγ ≃ 2.5, Ackermann et al. 2015). As the angular resolution of Fermi-LAT for sub-GeV photons is much worse than for GeV γ rays,3 the detection of the high-redshift soft γ-ray sources is challenging. Interestingly, a tenfold γ-ray flux increase and a harder-when-brighter spectral variability behavior have been detected in two γ-ray blazars beyond redshift 3 (Li et al. 2018). Therefore, the very distant blazars may be relatively easier to be detected in an outburst phase.

B3 1428+422 (z = 4.72, Hook & McMahon 1998), also known as GB 1428+4217, was identified in an optical spectroscopy search for high-redshift flat-spectrum radio sources. Its high X-ray luminosity (∼1047 erg s⁻¹, Fabian et al. 1997), the hard X-ray spectrum (Γx ≃ 1.5, Worsley et al. 2004), the radio morphology including a compact dominant core with high brightness temperature (Tb ≃ 5 × 10¹¹ K, Veres et al. 2010), and, more importantly, the significant radio and X-ray variability (Fabian et al. 1999; Worsley et al. 2006) strongly suggest that B3 1428+422 is a highly active high-redshift blazar. Searches for its γ-ray emission with the ∼7.5 years Fermi-LAT data have been performed, but no significant signal has been identified (Paliya et al. 2016; Ackermann et al. 2017). In this Letter, we analyze the ~9 years of Fermi-LAT data (Section 2), and report a promising γ-ray counterpart of B3 1428+422 (Section 3), along with some discussions (Section 4).

2. Data Analysis

The first 110 months (MJD 54683–58032) of SOURCE-type Fermi-LAT data (evclass = 128 and etype = 3), in the energy range of 0.1–500 GeV, are analyzed with the updated Fermi Science Tools package of version v11r5p3. The entire data set is filtered with gtselect and gtmktime tasks, by adopting a maximum zenith angle of 90° and “DATA_QUAL > 0” and “LAT_CONFIG == 1.” Then the unbinned likelihood algorithm implemented in the gtlike task is used to extract the γ-ray flux and spectrum. As B3 1428+422 is not included in any current γ-ray catalogs, a corresponding γ-ray source located at the radio position of B3 1428+422 with a single power-law (i.e., dN/dE ∝ E⁻Γ, where Γ is the spectral photon index) spectral template is added in the analysis model file. Meanwhile, all of the sources in the preliminary LAT 8 year Point Source List (FL8Y) within 15° of the target have been taken into account. Parameters of the FL8Y sources lying within 10° radius of interest (ROI) as well as two diffuse templates are left free, while others are fixed at FL8Y values. The test statistic (TS; TS = 2Δlog L, Mattox et al. 1996) is adopted to quantify the significance of a γ-ray source, where L represents the likelihood function between

3 http://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm
4 https://fermi.gsfc.nasa.gov/ssc/data/access/lat/fl8y/
models with and without the source. In the extraction of γ-ray light curves, weak background sources with TS values below 10 are removed from the model file. If new sources emerge in the subsequently generated TS residual map, TS values higher than 25 after the likelihood analysis, they are added into the updated background model and the likelihood fitting is re-performed.

3. Results

First, we perform a fit of the entire 110 month data. The TS map reveals two γ-ray sources not included in FL8Y, with TS values of 31 and 27, respectively. Their optimized locations are R.A. 215°31 and decl. 39.03 as well as R.A. 215°92 and decl. 40.72, with 95% C.L. radii of 0°15 and 0°34, respectively. The first source is likely associated with a radio-loud narrow-line Seyfert 1 FBQS J142106.0+385522, as reported in Paliya et al. (2018), while no promising low-energy counterpart has been found for the second source. Adopting the updated background model file including these two sources, an analysis of the entire 110 month data are carried out again. There is no evidence for a bright γ-ray source in the direction of B3 1428+422. The TS value of the potential weak γ-ray source (Γ fixed to 3.0) is rather small (TS = 3), in agreement with the result of a previous study (Paliya et al. 2016). This result holds when the photon index is fixed instead as 2.6 and 2.8, according to the photon indexes of high-redshift blazars detected by Fermi-LAT (Ackermann et al. 2017).

We then extract a half-year bin γ-ray light curve. When one source is not significantly detected by Fermi-LAT (i.e., TS < 10), a 95% confidential level (c.l.) upper limit is obtained by the pyLikelihood UpperLimits tool. Though the TS values in most time bins are rather small (<4), the ninth bin (MJD 56123−56303, i.e., from 2012 July 15th to 2013 January 11th) is distinguished by a high TS value of 26, which reveals the emergence of a new γ-ray transient source (see Figure 1(a)). Due to the limited spatial resolution of Fermi-LAT, such a rise of TS value could be caused by a flaring bright neighbor (e.g., Li et al. 2018). There are two known γ-ray sources nearby, FL8Y J1428.5+4240 (0°9 away) and FL8Y J1434.2+4205 (0°6 away); listed in FL8Y and associated to the blazars H 1426+428 and B3 1432+422, respectively. Their temporal behaviors are also examined. As shown in Figure 1(a), the appearance of the new γ-ray source does not coincide with any flaring event of its neighbors. Additional monthly light curves are extracted to identify the exact flaring epoch, see Figure 1(b). A period of 10 months is marked, in the time range between MJD 56123 and MJD 56423 (i.e., from 2012 July 15th to 2013 May 11th) Analyses for the pre-flare, flare, and post-flare epochs are performed. No significant signals are found in the pre-flare and post-flare phases (see Figures 2(a) and (c)). However, a strong γ-ray signal indeed appears at the direction of B3 1428+422 (see the corresponding TS maps in Figure 2(b)), confirming the result of the half-year bin γ-ray light curve.

A localization analysis of the new γ-ray source during the 10 month period provides the coordinates of R.A. 217°75 and decl. 41°99, with a 95% c.l. error radius of 0°33. The angular separation between the γ-ray position and the radio position of B3 1428+422 is 0°14 (see Figure 2(d)). We have also looked for other potential counterparts, especially blazar candidates included in the BZCAT list (Massaro et al. 2009) and high-frequency radio surveys (e.g., Myers et al. 2003; Healey et al. 2007, 2008). No other sources in these catalogs are found to be within the 95% c.l. γ-ray error radius. We use the Bayesian association method as well as the corresponding prior probability value for CRATES catalog (0.33, Abdo et al. 2010c) to calculate the association probability. Our result is 0.81, above the threshold of 0.8, suggesting a likely association. Adopting the updated γ-ray position, a single power-law function provides an acceptable description of the
\[ \frac{dN}{dE} = (2.16 \pm 0.44) \times 10^{-13} \left( \frac{E}{263 \text{ MeV}} \right)^{-2.95 \pm 0.24}, \]  

and the photon flux is \((1.92 \pm 0.45) \times 10^{-8} \text{ ph cm}^{-2} \text{ s}^{-1}\). If the \(\gamma\)-ray source is indeed associated with B3 1428+422, the apparent isotropic \(\gamma\)-ray luminosity in the flare phase should be \(8 \pm 2) \times 10^{48} \text{ erg s}^{-1}\) (here we take a \(\Lambda\)CDM cosmology with \(H_0 = 67 \text{ km s}^{-1} \text{ Mpc}^{-1}\), \(\Omega_m = 0.32\), and \(\Omega_\Lambda = 0.68\); Planck Collaboration et al. 2014). The corresponding TS value is 32 \((\approx 4.8\sigma)\). Because we have 11 trials, and hence a global significance, after correction of the trial factor can be estimated as

\[ \text{CDF}(\chi^2_{\text{def}=4}) = \text{CDF}(\chi^2_{\text{def}=1}, \sigma^2), \]

which is still \(>4\sigma\). By comparison with the 110 months averaged flux status, a 95\% c.l. upper limit of \(5 \times 10^{-9} \text{ ph cm}^{-2} \text{ s}^{-1}\), there is a significant \(\gamma\)-ray flux increase, though no explicit variability amplitude can be obtained due to the limited statistic.

Unlike FL8Y J1434.2+4205, the other nearby neighbor FL8Y J1428.5+4240 is significant (TS = 42) in the 10 month flaring epoch. Several tests are performed to evaluate its influence on our detection. No significant differences in the results obtained by using the model with one source or both sources are found. Moreover, because these two sources exhibit rather different spectral behaviors (\(\Gamma_{\text{neighbor}} \approx 1.5\) while \(\Gamma_{\text{target}} \approx 3.0\), the Fermi-LAT data below and above 1 GeV are analyzed separately. In the former case, the target is significant against the background (TS = 28), while the
neighbor turns out to be undetectable (TS < 4), as shown in the TS map (see Figure 3). The photon flux between 0.1 and 1 GeV is \((1.78 \pm 0.50) \times 10^{-8} \text{ph cm}^{-2} \text{s}^{-1}\) and the corresponding apparent luminosity is \((7 \pm 2) \times 10^{48} \text{erg s}^{-1}\), assuming a redshift of 4.72. The optimized location is R.A. 217° 70 and decl. 41° 87, with the 95% c.l. \(\gamma\)-ray error radius of 0° 41. Because the angular separation between the radio position of B3 1428+422 and the \(\gamma\)-ray location is 0° 22, the spatial association is confirmed. On the other hand, the TS of the target becomes rather low (TS \(\sim 4\)) in case of analysis in the 1–500 GeV energy range, which is in agreement with the rather soft spectrum of the target. In the fourteenth time bin of the half-year light curve the TS value of the target increased from 8 to 18 using the entire energy range or only the 0.1–1 GeV one, suggesting a mild activity in that period. Meanwhile, further 10 days bin light curves are extracted (see Figure 4). In one time bin (MJD 56155–56165, i.e., from 2012 August 15 to 25), the fit results in a TS = 23 (between 0.1 and 500 GeV) or TS = 18 (between 0.1 and 1 GeV), whereas the TS of the neighbor is lower than 1. Therefore, the new \(\gamma\)-ray source is robust rather than artificial caused by the neighbor FL8Y J1428.5+4240. In addition, localization analysis of this bin for the target gives an optimized location of R.A. 217° 57 and decl. 41° 66, with 95% c.l. \(\gamma\)-ray error radius of 0° 47, suggesting that B3 1428+422 is still within the error radius.

Considering the soft spectrum of the new \(\gamma\)-ray source, it should be still detectable with LAT data with a lower energy threshold (i.e., >60 MeV instead of >100 MeV). Following the data analysis procedure adopted in Ackermann et al. (2017), which is a summed likelihood analysis performed by the Fermipy software (Wood et al. 2017) based on four different point spread function event types with 15° ROI and customized zenith cut for each data set as well as handled energy dispersion, we indeed find a significant \(\gamma\)-ray source (TS = 35) there for the 10 month flaring epoch. Adopting a single power law as spectral template, the derived spectral index \((2.95 \pm 0.19)\)  is identical with what we find from the \(\gamma\)-ray location is 0° 22, the spatial association is confirmed. On the other hand, the TS of the target becomes rather low (TS \(\sim 4\)) in case of analysis in the 1–500 GeV energy range, which is in agreement with the rather soft spectrum of the target. In the fourteenth time bin of the half-year light curve the TS value of the target increased from 8 to 18 using the entire energy range or only the 0.1–1 GeV one, suggesting a mild activity in that period. Meanwhile, further 10 days bin light curves are extracted (see Figure 4). In one time bin (MJD 56155–56165, i.e., from 2012 August 15 to 25), the fit results in a TS = 23 (between 0.1 and 500 GeV) or TS = 18 (between 0.1 and 1 GeV), whereas the TS of the neighbor is lower than 1. Therefore, the new \(\gamma\)-ray source is robust rather than artificial caused by the neighbor FL8Y J1428.5+4240. In addition, localization analysis of this bin for the target gives an optimized location of R.A. 217° 57 and decl. 41° 66, with 95% c.l. \(\gamma\)-ray error radius of 0° 47, suggesting that B3 1428+422 is still within the error radius.

4. Summary and Discussion

Highly variable \(\gamma\)-ray emissions from high-redshift blazars (i.e., \(z > 2\)) have been detected by Fermi-LAT (Akyuz et al. 2013; Orienti et al. 2014; Abdo et al. 2015; D’Ammando & Orienti 2016; Paliya et al. 2016; Li et al. 2018). It is reasonable to record such violent behaviors because it is preferable to detect significantly beamed bright sources there due to the Malmquist bias. The typical peak \(\gamma\)-ray luminosity of these high-redshift sources is \(\sim 10^{50} \text{erg s}^{-1}\) (e.g., Li et al. 2018). PKS 1830–211 (\(z = 2.5\)) is the brightest high-redshift blazar detected so far, which has a daily peak flux of \(3 \times 10^{39} \text{erg s}^{-1}\) (Abdo et al. 2015). By comparison, the 10 day peaking luminosity of our target is \(\sim 3 \times 10^{49} \text{erg s}^{-1}\) assuming a redshift of 4.72. Together with its soft \(\gamma\)-ray spectrum, the robustness of the \(\gamma\)-ray signal and the spatial association between the \(\gamma\)-ray source and B3 1428+422, we suggest that the new transient GeV source may be the \(\gamma\)-ray counterpart of B3 1428+422.

High-redshift \(\gamma\)-ray sources, including blazars and \(\gamma\)-ray bursts (GRBs), are valuable targets because of the imprints of
extragalactic background light (EBL) in their γ-ray spectra (Abdo et al. 2010a). So far the most distant GRB detected by Fermi-LAT is GRB 080916C, at a photometric redshift of 4.35 (Greiner et al. 2009; Abdo et al. 2009). Therefore, B3 1428+422 could be the farthest high-energy γ-ray source detected so far. Horizon γ-ray photons (i.e., suffered significant EBL attenuation, \(\tau_{\gamma\gamma} = 1\)) have been detected in several blazars (e.g., Tanaka et al. 2013). Though energy of the most energetic γ-ray photons from our transient is about 2 GeV, which could not challenge the current EBL models \((E_{\text{horizon}} \sim 30\,\text{GeV}, \text{Finke et al. 2010})\), the presence of GeV sources at \(z > 4.5\) is indeed encouraging for such a purpose. Moreover, as there are no known γ-ray BL Lacs beyond redshift 3 right now (Liao et al. 2015), detections of high-redshift γ-ray FSRQs is also crucial for determining the high redshift end of γ-ray luminosity function (GLF) of blazars. In fact, PKS 0537—286 (\(z = 3.1\)) remains the most distant γ-ray source among the sample used to generate the current blazar GLFs (e.g., Ajello et al. 2012; Zeng et al. 2013). Therefore, the recently detected new high-redshift γ-ray FSRQs, especially the five new sources with redshifts between 3.4 and 4.3 (Ackermann et al. 2017) as well as B3 1428+422, should be embraced to update the blazar GLF (N.-H. Liao & H.-D. Zeng 2018, in preparation).

Compared with other high-redshift γ-ray blazars (Ackermann et al. 2017), the error radius of the γ-ray source tentatively associated with B3 1428+422 is relatively large due to its faintness and, more importantly, the rather soft spectrum, especially for the analyses of the 10 day time bin and the 10 month period with >60 MeV LAT data. This makes the association between the γ-ray source and the low-energy counterpart more difficult. Nevertheless, it is still helpful to examine whether or not there are only other suitable low-energy counterparts in the “enlarged” γ-ray error radii. Except for B3 1428+422, we find no suitable blazar candidates in the radio catalogs cited in the previous Section. The same holds if we choose the blazar candidates from the WISE blazar-like radio-loud sources (D’Abrusco et al. 2014) instead. We also notice that B3 1428+422 is the only flat-spectrum radio source in the region of the interest. However, National Radio Astronomy Observatory (NRAO) Very Large Array (VLA) Sky Survey (NVSS) images are only available for some of the radio sources included in the LAT error circle; therefore, it is not possible to determine a spectrum, and thus whether or not these are flat-spectrum radio sources.

Multiwavelength campaigns, including γ-ray observation as well as complementary observations from radio to X-rays, become a routine approach to probe the physical processes of...
AGN jets, and simultaneous γ-ray and optical flares have been frequently detected for FSRQs (e.g., Abdo et al. 2010b). The simultaneous detection of these flares would provide decisive proof of the association between the γ-ray source and its optical counterpart (e.g., Liao et al. 2016). Such important proof, however, is still lacking for all known γ-ray FSRQs beyond redshift 3. Due to their faint optical emission (typically \(R_{\text{mag}} > 20\)), many optical transient surveys are not deep enough (e.g., Drake et al. 2009). Nevertheless, strong optical flares are found from one of those sources, NVSS J163547+362930 (\(z = 3.6\)), based on archival Palomar Transient Factory (PTF) data (Li et al. 2018). Therefore, we examined the PTF data\(^5\) of B3 1428+422 (\(\gamma_{\text{SDSS, mag}} = 21\), Pâris et al. 2014). No PTF observations are available in 2012 August, when the intense γ-ray flare appeared and no significant optical flare of B3 1428+422 can be identified at other times. A confirmed association with the lower-energy counterpart will be established with future simultaneous multi-frequency observations in the period of the high γ-ray activity of the new transient. With upcoming wide-deep-fast sky survey facilities, such as the Large Synoptic Survey Telescope (Ivezic et al. 2008) as well as other future observational facilities in time domain (e.g., the Wide-Field InfraRed Survey Telescope, Green et al. 2012; the Einstein Probe, Yuan et al. 2015), a comprehensive broadband dynamic view of high-redshift γ-ray sources will be achieved.

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References

Abdo, A. A., Ackermann, M., Ajello, M., et al. 2010a, ApJ, 723, 1082
Abdo, A. A., Ackermann, M., Ajello, M., et al. 2010b, Nature, 463, 919
Abdo, A. A., Ackermann, M., Ajello, M., et al. 2010c, ApJS, 188, 405
Abdo, A. A., Ackermann, M., Ajello, M., et al. 2015, ApJ, 799, 143
Abdo, A. A., Ackermann, M., Arimoto, M., et al. 2009, Sci, 323, 1688
Acero, F., Ackermann, M., Ajello, M., et al. 2015, ApJS, 218, 23
Ackermann, M., Ajello, M., Atwood, W. B., et al. 2015, ApJ, 810, 14
Ackermann, M., Ajello, M., Baldini, L., et al. 2017, ApJL, 837, L5
Ajello, M., Shaw, M. S., Romani, R. W., et al. 2012, ApJ, 751, 108
Akyuz, A., Thompson, D. J., Donato, D., et al. 2013, A&AA, 556, A71
Blandford, R. D., & Rees, M. J. 1978, in Pittsburgh Conf. BL Lac Objects, ed. A. M. Wolfe (Pittsburgh, PA: Univ. Pittsburgh Press), 328
D’Abrusco, R., Massaro, F., Paggi, A., et al. 2014, ApJS, 215, 14
D’Ammando, F., & Orienti, M. 2016, MNRAS, 455, 1881
Drake, A. J., Djorgovski, S. G., Mahabal, A., et al. 2009, ApJ, 696, 870
Fabian, A. C. 2012, ARA&A, 50, 455
Fabian, A. C., Brandt, W. N., McMahon, R. G., & Hook, I. M. 1997, MNRAS, 291, L5
Fabian, A. C., Celotti, A., Pooley, G., et al. 1999, MNRAS, 308, L6
Finke, J. D., Razzakez, S., & Dermer, C. D. 2010, ApJ, 712, 238
Flesch, E. W. 2015, PASA, 32, e010
Ghisellini, G., Della Ceca, R., Volonteri, M., et al. 2010, MNRAS, 405, 387
Ghisellini, G., Sharrato, T., Tagliaferri, G., et al. 2014, MNRAS, 440, L111
Green, J., Schechter, P., Balatay, C., et al. 2012, arXiv:1208.4012
Greiner, J., Clemens, C., Krühler, T., et al. 2009, A&AA, 498, 89
Healey, S. E., Romani, R. W., Cotter, G., et al. 2008, ApJS, 175, 97
Healey, S. E., Romani, R. W., Taylor, G. B., et al. 2007, ApJS, 171, 61
Hook, I. M., & McMahon, R. G. 1998, MNRAS, 294, L7
Ivezic, Z., Tyson, J. A., Abel, B., et al. 2008, arXiv:0805.2366
Li, S., Xia, Z-Q., Liang, Y.-F., Liao, N.-H., & Fan, Y.-Z. 2018, ApJ, 853, 159
Liao, N.-H., Bai, J.-M., Wang, J.-G., et al. 2015, RAA, 15, 313
Liao, N.-H., Xin, Y.-L., Fan, X.-L., et al. 2016, ApJS, 226, 17
Mattox, J. R., Bertsch, D. L., Chiang, J., et al. 1996, ApJ, 461, 396
Myers, S. T., Jackson, N. J., Browne, I. W. A., et al. 2003, MNRAS, 341, 1
Orienti, M., D’Ammando, F., Giroletti, M., et al. 2014, MNRAS, 444, 3040
Paliya, V. S., Ajello, M., Rakshit, S., et al. 2018, ApJL, 853, L2
Paliya, V. S., Parker, M. L., Fabian, A. C., & Stalin, C. S. 2015, ApJ, 825, 74
Pâris, I., Petitjean, P., Aubourg, É., et al. 2014, A&A, 563, A54
Planck Collaboration, Ade, P. A. R., Aghanim, N., et al. 2014, A&A, 571, A16
Romani, R. W., Sowards-Emmerd, D., Greenhill, L., & Michelson, P. 2004, ApJL, 610, L9
Sharrato, T., Ghisellini, G., Nardini, M., et al. 2012, MNRAS, 426, L91
Tanaka, Y. T., Cheung, C. C., Inoue, Y., et al. 2013, ApJ, 777, L18
Urry, C. M., & Padovani, P. 1995, PASP, 107, 803
Veres, P., Frey, S., Paragi, Z., & Gurvits, L. I. 2010, A&A, 521, A6
Volonteri, M. 2010, A&ARv, 18, 279
Wood, M., Caputo, R., Charles, E., et al. 2017, arXiv:1707.09551
Worsley, M. A., Fabian, A. C., Celotti, A., & Iwasawa, K. 2004, MNRAS, 350, L67
Worsley, M. A., Fabian, A. C., Pooley, G. G., & Chandler, C. I. 2006, MNRAS, 368, 844
Yi, W.-M., Wang, F., Wu, X.-B., et al. 2014, ApJL, 795, L29
Yuan, W., Zhang, C., Peng, H., et al. 2015, arXiv:1506.07735
Zeng, H., Yan, D., & Zhang, L. 2013, MNRAS, 431, 997

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\(^5\) http://irsa.ipac.caltech.edu/applications/ptf/