Long-Term Infrared Variability and Color Variation of Gamma-Ray Loud Narrow-Line Seyfert 1 Galaxies: Postprint

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Abstract

Some narrow-line Seyfert 1 galaxies have been found to exhibit GeV gamma-ray emission (gamma-ray loud) and have consequently attracted continued attention. To date, the literature has reported 22 gamma-ray loud narrow-line Seyfert 1 galaxies, along with 3 additional high-confidence candidates. Utilizing the Wide-field Infrared Survey Explorer (WISE) data platform, simultaneous photometric data in two infrared bands, W1 (3.4 m) and W2 (4.6 m), were obtained for these sources covering the period from January 2010 to December 2019. The parameter V and the normalized excess variance method were employed to analyze their long-term variability. The results show that 24 sources display long-term brightness (W1 magnitude) variations, while 17 sources exhibit long-term color (W1-W2) variations. By investigating the correlation between color and magnitude, 7 sources were found to exhibit a redder-when-brighter (RWB) phenomenon, and 4 sources display a bluer-when-brighter (BWB) phenomenon. Finally, possible explanations and implications of these color variations are briefly discussed.

Full Text

The Long-term Infrared Brightness and Color Variabilities of γ-ray-loud Narrow-line Seyfert 1 Galaxies

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Abstract

The detection of GeV γ-rays from some narrow-line Seyfert 1 galaxies (γ-ray-loud NLS1s) has received increasing attention. Up to now, the literature has reported 22 γ-ray-loud NLS1s and another 3 high-confidence candidates. Using the data platform of the Wide-field Infrared Survey Explorer (WISE), we derived simultaneous photometric data in the W1 (3.4 m) and W2 (4.6 m) bands (from January 2010 to December 2019) for these sources. We then analyzed their long-term variability via the parameter V and the normalized excess variance σ^2_{NXS} methods. It was found that 24 sources showed long-term brightness (W1 magnitude) variabilities, and 17 sources showed long-term color (W1-W2) variabilities. When studying the correlation between color and magnitude, we found that 7 sources exhibited a redder-when-brighter (RWB) trend, while 4 sources exhibited a bluer-when-brighter (BWB) trend. Finally, the possible causes of these color changes and their implications are briefly discussed.

Keywords: Seyfert galaxy; Gamma-ray; Infrared variability; Statistical

0 Introduction

Seyfert galaxies represent a class of low-luminosity active galactic nuclei (AGN) whose host galaxies are readily observable, in contrast to quasars [1]. Based on their emission-line properties, they are divided into two subclasses: Seyfert 1 and Seyfert 2 galaxies [2]. The former exhibit broad permitted lines with full width at half maximum (FWHM) exceeding 2000 km s^{-1}, while the latter show permitted lines with widths comparable to their forbidden lines, typically less than 1000 km s^{-1}. In the unified model of AGN, both types share the same central engine structure, with their observational differences arising from orientation effects. Seyfert 2 galaxies are viewed at larger inclination angles, causing the broad-line region emission to be obscured by an outer, optically thick dusty torus along the line of sight [3-4].

Narrow-line Seyfert 1 galaxies (NLS1s) constitute a particularly unique subclass of Seyfert galaxies. The original definition by Osterbrock & Pogge [5] specifies that NLS1s have relatively narrow Hβ emission line widths (FWHM $<$ 2000 km s^{-1}), weak [O III] \$ 5007$relativetoH$ \$ ([O III]/H$\beta < 3$), and strong Fe II emission, along with steep soft X-ray spectra. It is generally believed that NLS1s harbor relatively small central black hole masses and high Eddington ratios [6-9]. The vast majority of NLS1s are radio-quiet (radio loudness parameter $R < 10$), with only about 2.5% being radio-loud ($R > 10$) [10-12]. Over the past decade, γ-ray-loud NLS1s (γ-NLS1s) discovered by the Fermi Large Area Telescope (Fermi/LAT) have attracted widespread and sustained attention in the astronomical community, providing direct evidence for the presence of relativistic jets in these sources. γ-NLS1s may exhibit observational characteristics similar to blazars, such as compact radio cores, very high brightness temperatures, rapid and large-amplitude variability, flat radio spectra, and double-peaked broadband spectral energy distributions [13-16].

To date, the number of known γ-NLS1s remains small, but systematic studies of their observational and statistical properties are crucial for understanding jet formation, the connection between accretion disk-corona-jet systems, gamma-ray emission mechanisms and regions, and galaxy evolution [14]. In this work, based on the largest currently available sample of γ-NLS1s, we systematically investigate their long-term infrared brightness and color variations to obtain useful clues about infrared emission mechanisms.

1.1 Sample

Paliya [13] compiled all currently known γ-NLS1s, comprising 22 sources. Additionally, Lähteenmäki et al. [17] identified 3 further high-confidence γ-NLS1 candidates. These 25 sources constitute our analysis sample. Columns (2)-(5) of Table 1 provide detailed information, including source names, right ascension and declination in degrees, and redshift z.

1.2 WISE Survey

The Wide-field Infrared Survey Explorer (WISE) is a NASA space telescope launched in December 2009 to map the entire sky in infrared wavelengths [18]. WISE carries a 40-cm infrared telescope operating in four bands: 3.4, 4.6, 12, and 22 m (designated W1, W2, W3, and W4), with spatial resolutions of 6.1, 6.4, 6.5, and 12 arcseconds, respectively. Before September 30, 2010, WISE conducted all-sky surveys in W1-W4 or W1-W3 bands, after which it continued only in W1 and W2 bands for the Near-Earth Object Wide-field Infrared Survey Explorer (NEOWISE) mission until entering hibernation in February 2011. In October 2013, WISE was reactivated and has since continued the NEOWISE-R mission in W1 and W2 bands to the present day [19-20].

WISE completes an all-sky survey every six months. Over approximately one day, it completes 15 orbits, yielding light curves with multiple photometric data points (typically 12) for target sources on daily timescales [21]. Compared to the previous Infrared Astronomical Satellite (IRAS), WISE's sensitivity is 100 times greater, providing unprecedented opportunities to study the infrared properties of AGN [22].

1.3 Light Curves

Using the NASA/IPAC Infrared Science Archive (IRSA) with a search radius of 3 arcseconds, we first obtained W1 and W2 band photometric data for the 25 sources from January 2010 to December 2019. It should be emphasized that W3 and W4 band data are much sparser and have relatively poorer photometric accuracy, and therefore were not included in our analysis. We then screened the data to remove poor-quality measurements using the following criteria: nb

≤ 2, na = 0, moon_{masked} = '00' , cc_{flags} = '00' , w1sat = 0, w2sat = 0, w1snr ≥ 7, w2snr ≥ 5, w1rchi2 < 10, w2rchi2 < 10, qual_{frame} > 0, qi_{fact} > 0, saa_{sep} > 0, and sso_{flag} = 0. Additionally, we removed data points with only magnitude upper limits in either W1 or W2, as well as points with magnitude errors (w1sigmpro, w2sigmpro) exceeding 0.2 mag. Details of the photometric data quality can be found in the official WISE documentation. This process yielded simultaneous W1 and W2 light curves for all 25 sources. Each source was observed during 13-15 epochs (see column 6 of Table 1), with each observational epoch containing an average of 14 W1/W2 photometric measurements over an average duration of approximately 1.3 days.

To investigate the long-term infrared brightness and color variations of γ-NLS1s, we performed weighted averaging of the data for each observational epoch following standard procedures [23]. For a time series dataset x_i with weights $\omega_i = 1/\sigma_i^2$, the weighted mean is given by equation (1) and its standard error by equation (2). Using these formulas, we calculated the epoch-averaged W1 magnitude and its standard error, as well as the epoch-averaged color (W1-W2) and its standard error for each source (Table 2 provides examples for two sources), thereby obtaining the long-term variation curves for W1 magnitude and color (W1-W2). Figure 1 [Figure 1: see original paper] illustrates the process for PMN J0948+0022, showing the W1/W2 light curves for all epochs (blue points for W1 magnitude, red points for W2 magnitude), the epoch-averaged W1 magnitude light curve, and the epoch-averaged color (W1-W2) variation curve.

2 Methods and Results

We employed two methods to investigate whether the sample sources exhibit long-term brightness and color variations.

2.1 Parameter V

The parameter V, defined by McLaughlin et al. [24], is widely used to quantify the probability of variability. This parameter is derived from the chi-square value of the light curve as shown in equation (3), where y_i represents the observed magnitude (or color), $\sigma_{err,i}$ the magnitude (or color) error, $\bar{y}$ the mean magnitude (or color), and N the number of data points. The probability of variability is then given by equation (4), where Γ is the incomplete gamma function [25]. Larger V values indicate higher probabilities of variability. The commonly adopted criterion in the literature is $V > 3.1$, corresponding to a variability probability exceeding 95% [26].

2.2 Normalized Excess Variance

The normalized excess variance (σ^2_{NXS}) is frequently used to quantify variability amplitude, where "excess" indicates that the variance due to observational errors has been removed from the total variance [27]. It is defined by equation (5), where $\sigma_{err,i}$ represents the observational errors. When measurement errors are large, σ^2_{NXS} may become negative. Following Sánchez et al. [26], we define $\Delta = \sigma^2_{NXS} - \sigma^2_{err}$ to indicate that the error-corrected variability amplitude exceeds zero.

2.3 Results

Using the two methods described above, we examined the long-term brightness and color variations of our sample sources. A source was considered to exhibit statistically significant brightness (color) variation if its light curve simultaneously satisfied $V > 3.1$ and $\Delta > 0$.

The results revealed that: (1) except for 3C 286, all other γ-NLS1s showed long-term brightness variations; (2) 17 γ-NLS1s exhibited long-term color variations. Detailed results are presented in columns (7) and (8) of Table 1.

The advantage of using WISE to study infrared color variations lies in the simultaneous observation of W1 and W2 bands. To further understand the long-term color variations of our sample sources, we constructed color-magnitude diagrams with W1 magnitude on the x-axis and color (W1-W2) on the y-axis. Based on the brightness and color variability analysis, we constructed color-magnitude diagrams only for the 17 γ-NLS1s that showed both long-term brightness and color variations. Using weighted least-squares fitting that accounts for errors in both color and magnitude [25], we fitted linear relationships of the form $(W1 - W2) = A \times W1 + B$, where A is the slope and B the intercept. Columns (3)-(6) of Table 3 present the linear fitting results for these 17 sources. The slope A of the best-fit line serves as a measure of spectral shape variation, with its distribution shown in Figure 2 [Figure 2: see original paper]. Additionally, we calculated the Spearman rank correlation coefficient (r_s) and chance probability (p) between W1 magnitude and color (W1-W2), using this non-parametric statistic due to the non-normal distribution of the data. The results are listed in columns (7) and (8) of Table 3, with r_s and p values respectively. Following Anjum et al. [28], we characterized the color variation trends as: (1) if $A > 0$ and $p < 0.05$, the source shows a bluer-when-brighter (BWB) trend; (2) if $A < 0$ and $p < 0.05$, the source shows a redder-when-brighter (RWB) trend. According to these criteria, 4 γ-NLS1s exhibited significant BWB trends (Figure 3 [Figure 3: see original paper]), while 7 γ-NLS1s showed significant RWB trends (Figure 4 [Figure 4: see original paper]).

The infrared emission from AGN may include multiple components, both thermal and non-thermal, with their relative contributions depending strongly on the AGN type and wavelength. In AGN, a dusty torus absorbs ultraviolet/optical radiation from the accretion disk and re-emits this energy as infrared radiation, with wavelengths determined by dust temperature. The dust temperature reaches approximately 1500 K, with emission peaking at a few microns [29]. In addition to the dusty torus, contributions from the host galaxy and jet synchrotron radiation (for radio-loud AGN) must also be considered [30].

Rakshit et al. [31] utilized WISE W1/W2 data to study the long-term mid-infrared color (W1-W2) variations of 492 radio-detected NLS1s, finding that 69% showed color variations exceeding 0.1 mag. Among these, 27% exhibited RWB trends and 42% showed BWB trends. Within a two-component framework (AGN emission + host galaxy emission), they provided possible explanations for these trends. RWB trends tend to appear when AGN emission dominates (bright states), while BWB trends are favored when AGN and host galaxy emissions are comparable (faint states). In this work, we focus on the more special subclass of γ-NLS1s and investigate their long-term brightness and color variations. Notably: (1) All 9 γ-NLS1s included in Rakshit et al. [31] are present in our sample (marked with "†" in Table 1). For 8 of these, our results are fully consistent with theirs (SBS 0846+513, NVSS J093241+530633, PMN J0948+0022, PKS 1502+036, TXS 1518+423, and SDSS J211852.96-073227.5 show significant RWB trends; GB6 J0937+5008 and PMN J2118+0013 show no significant RWB or BWB trends). Rakshit et al. [31] reported a long-term RWB trend for NVSS J142106+385522, but our analysis indicates this source shows significant long-term brightness variation without significant color variation, so we did not perform color-magnitude fitting or correlation analysis for it. (2) Using WISE data through December 2019, our analysis includes 2-5 more observational epochs per source than Rakshit et al. [31]. Our results demonstrate that γ-NLS1s exhibit both RWB and BWB trends, with 68% (17/25) showing statistically significant long-term color (W1-W2) variations, consistent with Rakshit et al. [31]. Among these, 41% (7/17) show RWB trends and 24% (4/17) show BWB trends, suggesting that γ-NLS1s have a stronger tendency toward RWB variations. This may result from the prominent jet emission and higher accretion rates in γ-NLS1s, which more easily dominate the overall radiation. It should be emphasized that the currently known sample of γ-NLS1s is small, and our comparative analysis provides only preliminary "clues" about the infrared emission in these sources. Our hypotheses require verification through future analyses of larger samples. Additionally, combining other methods (such as rapid variability studies and spectral energy distribution fitting) would better enable exploration and quantification of the relative contributions from different components to the infrared emission.

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References

[1] PETERSON B M. An Introduction to Active Galactic Nuclei[M]. London: Cambridge University Press, 1997: 21-23

[2] KHACHIKIAN E, WEEDMAN D W. An atlas of Seyfert galaxies[J]. The Astrophysical Journal, 1974, 192: 581-589

[3] NETZER H. Revisiting the Unified Model of Active Galactic[J]. Annual Review of Astronomy and Astrophysics, 2015, 53: 365-408

[4] URRY C M, PADOVANI P. Unified Schemes for Radio-Loud Active Galactic Nuclei[J]. Publications of the Astronomical Society of the Pacific, 1995, 107: 803-845

[5] OSTERBROCK D E, POGGE R W. The spectra of narrow-line Seyfert 1 galaxies[J]. The Astrophysical Journal, 1985, 297: 166-176

[6] MATHUR S. Narrow-line Seyfert 1 galaxies and the evolution of galaxies and active galaxies[J]. Monthly Notices of the Royal Astronomical Society, 2000, 314(4): 17-20

[7] COLLIN S, KAWAGUCHI T. Super-Eddington accretion rates in Narrow Line Seyfert 1 galaxies[J]. Astronomy and Astrophysics, 2004, 426: 797-808

[8] KOMOSSA S, XU D. Narrow-Line Seyfert 1 Galaxies and the MBH-σ Relation[J]. The Astrophysical Journal Letters, 2007, 667(1):

[9] PETERSON B M, MCHARDY I M, WILKES B J, et al. X-Ray and Optical Variability in NGC 4051 and the Nature of Narrow-Line Seyfert 1 Galaxies[J]. The Astrophysical Journal, 2000, 542, 161

[10] ZHOU H, WANG T, YUAN W, et al. A Comprehensive Study of 2000 Narrow Line Seyfert 1 Galaxies from the Sloan Digital Sky Survey. I. The Sample[J]. The Astrophysical Journal Supplement, 2006, 166(1): 128-153

[11] YUAN W, ZHOU H Y, KOMOSSA S, et al. A Population of Radio-Loud Narrow-Line Seyfert 1 Galaxies with Blazar-Like Properties?[J]. The Astrophysical Journal, 2008, 685(2): 801-827

[12] KOMOSSA S, VOGES W, XU D, et al. Radio-loud Narrow-Line Type 1 Quasars[J]. The Astronomical Journal, 2006, 132(2):

[13] PALIYA V S. Gamma-ray emitting narrow-line Seyfert 1 galaxies: Past, present, and future[J]. Journal of Astrophysics and Astronomy, 2019, 40(5): 39

[14] D' AMMANDO F. Relativistic Jets in Gamma-Ray-Emitting Narrow-Line Seyfert 1 Galaxies[J]. Galaxies, 2019, 7(4): 87

[15] ACKERMANN M, AJELLO M, ATWOOD W B, et al. The Third Catalog of Active Galactic Nuclei Detected by the Fermi Large Area Telescope[J]. The Astrophysical Journal, 2015, 810(1): 14

[16] PALIYA V S, STALIN C S, Ravikumar C D. Fermi Monitoring of Radio-Loud Narrow-Line Seyfert 1 Galaxies[J]. The Astronomical Journal, 2015, 149(2): 41

[17] LÄHTEENMÄKI A, JÄRVELÄ E, RAMAKRISHNAN V, et al. Radio jets and gamma-ray emission in radio-silent narrow-line Seyfert 1 galaxies[J]. Astronomy and Astrophysics, 2018, 614: 1
[18] WRIGHT E L, EISENHARDT P R M, MAINZER A K, et al. The Wide-field Infrared Survey Explorer (WISE): Mission Description and Initial On-orbit Performance[J]. The Astronomical Journal, 2010, 140(6): 1868-1881
[19] MAINZER A, BAUER J, GRAV T, et al. Preliminary Results from NEOWISE: An Enhancement to the Wide-field Infrared Survey Explorer for Solar System Science[J]. The Astrophysical Journal, 2011, 731(1): 53
[20] MAINZER A, BAUER J, CUTRI R M, et al. Initial Performance of the NEOWISE Reactivation Mission[J]. The Astrophysical Journal, 2014, 792(1): 30
[21] JIANG N, ZHOU H, HO L C, et al. Rapid Infrared Variability of Three Radio-loud Narrow-line Seyfert 1 Galaxies: A View from the Wide-field Infrared Survey Explorer[J]. The Astrophysical Journal Letters, 2012, 759(2): 31
[22] ASSEF R J, STERN D, NOIROT G, et al. The WISE AGN Catalog[J]. The Astrophysical Journal Supplement, 2018, 234: 23
[23] BEVINGTON P R. Data Reduction and Error Analysis for the Physical Sciences. New York: McGraw-Hill, 1969: 57-58
[24] MCLAUGHLIN M A, MATTOX J R, CORDES J M, et al. Variability of CGRO/EGRET Gamma-Ray Sources[J]. The Astrophysical Journal, 1996, 473: 763-772
[25] PRESS W H, TEUKOLSKY S A, VETTERLING W T, et al. Numerical Recipes: The Art of Scientific Computing[M]. London: Cambridge University Press, 1992: 209-213, 660-664
[26] SÁNCHEZ P, LIRA P, CARTIER R, et al. Near-infrared Variability of Obscured and Unobscured X-Ray-selected AGNs in the COSMOS Field[J]. The Astrophysical Journal, 2017, 849(2): 110
[27] VAUGHAN S, EDELSON R, WARWICK R S, et al. On characterizing the variability properties of X-ray light curves from active galaxies[J]. Monthly Notices of the Royal Astronomical Society, 2003, 345(4): 1271-1284
[28] ANJUM A, STALIN C S, RAKSHIT S, et al. Mid-infrared variability of gamma-ray emitting blazars[J]. Monthly Notices of the Royal Astronomical Society, 2020, 494(1): 764-774
[29] FRITZ J, FRANCESCHINI A, HATZIMINAOGLOU E. Revisiting the infrared spectra of active galactic nuclei with a new torus emission model[J]. Monthly Notices of the Royal Astronomical Society, 2006, 366(3): 767-786
[30] CACCIANIGA A, ANTÓN S, BALLO L, et al. WISE colours and star formation in the host galaxies of radio-loud narrow-line Seyfert 1[J]. Monthly Notices of the Royal Astronomical Society, 2015, 451(2): 1795-1805
[31] RAKSHIT S, JOHNSON A, STALIN C S, et al. WISE view of narrow-line Seyfert 1 galaxies: mid-infrared colour and variability[J]. Monthly Notices of the Royal Astronomical Society, 2019, 483(2): 2362-2370

Note: Figure translations are in progress. See original paper for figures.