

## VIOLENT INTRANIGHT OPTICAL VARIABILITY OF A RADIO-LOUD NARROW-LINE SEYFERT 1 GALAXY: SDSS J094857.3+002225

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### ABSTRACT

SDSS J094857.3+002225 is a very radio-loud narrow-line Seyfert 1 (NLS1) galaxy. Here, we report our discovery of the intranight optical variability (INOV) of this galaxy through the optical monitoring in the *B* and *R* bands that covered seven nights in 2009. Violent rapid variability in the optical bands was identified in this RL-NLS1 for the first time, and the amplitudes of the INOV reaches 0.5 mag in both the *B* and *R* bands on the timescale of several hours. The detection of the INOV provides a piece of strong evidence supporting the fact that the object carries a relativistic jet with a small viewing angle, which confirms the conclusion drawn from the previous multi-wavelength studies.

**Key words:** galaxies: active – galaxies: jets – galaxies: photometry – galaxies: Seyfert – quasars: individual (SDSS J094857.3+002225)

*Online-only material:* color figure

### 1. INTRODUCTION

Narrow-line Seyfert 1 galaxies (NLS1s) are a special and interesting group of active galactic nuclei (AGNs). They show narrow optical Balmer emission lines ( $\text{FWHM}(\text{H}\beta) < 2000 \text{ km s}^{-1}$ ), weak  $[\text{O III}]\lambda 5007$  emission ( $[\text{O III}]/\text{H}\beta < 3$ ), strong Fe II emission, and soft X-ray excess (Pogge 2000; Osterbrock & Pogge 1985; Sulentic et al. 2000; Boller et al. 1996; Boller 1997).

NLS1s show remarkable radio-loud/radio-quiet bimodality (Laor 2000). Only 7% of NLS1s are radio-loud objects (Zhou et al. 2003; Komossa et al. 2006). The fraction is much smaller than that found in QSOs. Very radio-loud NLS1s (RL-NLS1s,  $R > 100$ ) are even much fewer ( $\sim 2.5\%$ ; Komossa 2008), where the radio loudness  $R$  is commonly defined as the flux ratio of radio to optical at  $\lambda 4400$  (Kellermann et al. 1989). So far, it is still a puzzle why RL-NLS1s are so scarce. At present, the origin of RL-NLS1s is also still poorly understood.

A few efforts have been made in the past few years to understand the nature of RL-NLS1s. Yuan et al. (2008) found that the broadband spectra of some RL-NLS1s are similar to those of high-energy-peaked BL Lac objects, and suggested that some of them may be BL Lac objects actually. Basing upon the recent observation taken by *Fermi* satellite, some RL-NLS1s display a hard X-ray component suggesting the presence of relativistic jets on the line of sight (Foschini et al. 2009; Abdo et al. 2009a).

The presence of the relativistic jets motivates us to search for intranight optical variability in some RL-NLS1s, because of the well-known beaming effect (e.g., Wagner & Witzel 1995). Komossa et al. (2006) argued that SDSS J094857.3+002225 is a right candidate for searching for RL-NLS1s with beaming effect. The object is a very radio-loud NLS1 at  $z = 0.585 \pm 0.001$ . The reported radio loudness derived from the radio flux at 5 GHz ranges from 194 to 1982 (Zhou et al. 2003; Komossa et al. 2006; Abdo et al. 2009a). It is in the CRATES catalog as a flat-spectral radio source (Healey et al. 2007). The simultaneous observations taken by both *Swift* and *Fermi* also suggest that the broadband

spectral energy distribution is similar to those of flat-spectral radio quasars (Abdo et al. 2009a; Zhou et al. 2003). Recent photometry from the Guide Star Catalogs 2.21 is  $B_J$  (GSC2.21) = 18.83 mag (Zhou et al. 2003).

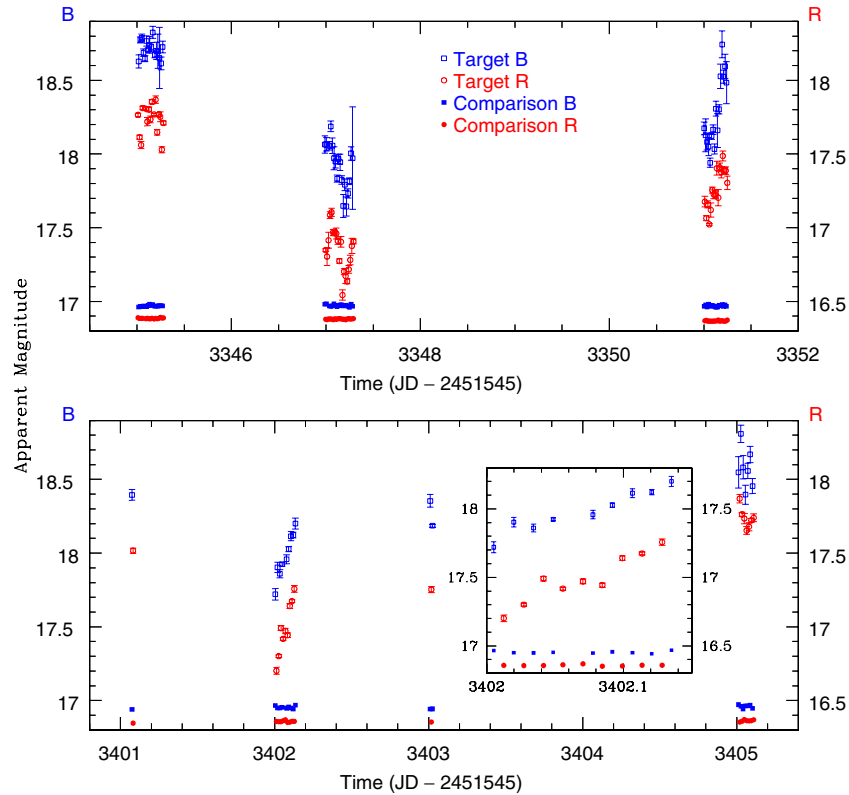
Previous studies revealed multi-wavelength variabilities in the object at timescales from day to year. Previous radio observations indicate its fluctuation in the radio band on the timescale from weeks to years (Abdo et al. 2009a). Zhou et al. (2003) also said that the object shows long-term variability in both the radio and optical bands. The amplitude of the variation in the radio can be 60% within a year. The long-term variability amplitude may be about 1 mag in the optical band. The latest multi-wavelength campaign carried out by Abdo et al. (2009b) discovered an optical variability on day timescales. Dramatic flux variabilities in both X-rays and radio 37 GHz were also found in the study.

In this Letter, we report an optical monitor for the RL-NLS1 SDSS J094857.3+002225. The monitor was designed to search for intranight optical variability (INOV) in the object. The INOV should be detected if the object indeed hosts a relativistic jet beaming toward the observers.

### 2. OBSERVATIONS AND DATA ANALYSIS

Our observations were carried out at the Xinglong Observatory of National Astronomical Observatories, Chinese Academy of Sciences (NAOC), using the 80 cm TNT telescope. The telescope is a Cassegrain system with a  $f/10$  beam. A liquid nitrogen cooled PI VA1300B  $1300 \times 1340$  LN CCD was used as the detector that covers  $\sim 11 \times 11$  arcmin<sup>2</sup> of the sky. Each pixel of the CCD corresponds to  $\sim 0.5 \times 0.5$  arcsec<sup>2</sup>. Gain and read-out noise of the CCD is 2.3 electrons ADU<sup>-1</sup> and 5 electrons, respectively. The standard Johnson *B*- and *R*-band filters were used in the observations.

We monitored the object on seven moonless nights in 2009. They are February 27, March 1, 5, and April 24–26, and 28. The typical exposure time is 600 s for each frame. Continuous monitoring for this object was run as long as possible in each night. The sky flat-field frames in both *B* and *R* passbands



**Figure 1.** Differential light curves for SDSS J094857.3+002225. The upper and lower panels give curves obtained on the nights of 2009 February 27 to March 5 and April 24 to 28, respectively. (The corresponding dates on the time-axis in this figure are 3345–3351 and 3401–3405, respectively.) The inset shows the details of the variability of the source within 4 hr on the night of April 25. The blue open squares and red open circles represent the apparent magnitude of SDSS J094857.3+002225 in the *B* and *R* bands, respectively. The blue filled squares and red filled circles represent the magnitude of one of the comparison stars in the *B* and *R* bands, respectively. The points of the comparison stars have been shifted vertically for comparison.

(A color version of this figure is available in the online journal.)

were obtained before and after each observation run during the twilight time. Dark frames are not needed because the temperature of the detector is so low ( $\sim -110^\circ\text{C}$ ) that the dark electrons can be entirely ignored.

The observed data are preliminarily reduced through the standard routine by IRAF package,<sup>3</sup> including bias and flat-field corrections. Several bright comparison stars are selected from the same CCD frame to calculate differential light curve. Because the comparison stars are brighter than the object, several check stars with brightness comparable to the object are selected to assess the errors in photometry. The instrumental magnitudes of the object and of those selected stars are calculated by the APPHOT task. The aperture photometry is adopted because the object is a point-like source without extended emission. In each frame, the FWHM of the object is comparable with those of the field stars. The circular aperture radius twice of the mean FWHM of the field stars was therefore adopted in our calculations. All the results reported below are based on these radii.

### 3. RESULTS

Our observations can be divided into two parts. Both of them contain about 1 week. The source was well monitored on the nights of 2009 February 27, March 1, March 5, April 25, and

April 28. (The corresponding dates on the time-axis of Figure 1 are 3345, 3347, 3351, 3402, and 3405, respectively.) There were no or only scarce data on the other nights because of the bad weather. The intrinsic brightness of the comparison stars was obtained<sup>4</sup> and the Sloan Digital Sky Survey (SDSS) database was used. Then the apparent magnitudes of the object can be calculated from the differential instrumental magnitudes. The light curves of the observations are plotted in Figure 1. The upper two light curves show the variation of the object in the *B* (by blue solid squares) and *R* (by red solid circles) bands. The corresponding variations of the comparison stars are plotted by the bottom two light curves. The fluctuations of the comparison stars are not larger than 0.05 mag. The error bars overplotted on the light curve are estimated from the selected check stars with brightness comparable to that of the object.

In addition to a long-term variation with amplitude about 1 mag, the obtained light curves indicate that there were several nights during which the INOV can be clearly identified in the object in both the *B* and *R* bands. The variations in both bands are similar to each other.

The amplitudes of the rapid variations are so large that the short-term variability is quite obvious on 2009 March 1, 5, and April 25. In particular, the weather was relatively good on 2009 March 1 and April 25, which results in relatively smaller error bars. For example, the typical error bars on April 25 are 0.05 mag and 0.02 mag in the *B* and *R* bands, respectively. The

<sup>3</sup> IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation; <http://iraf.noao.edu>.

<sup>4</sup> <http://www.sdss.org/dr6/algorithms/sdssUBVRITransform.html#Lupton2005>

brightness of the object changes about 0.5–0.6 mag in both bands within several hours on the same night. The inset in Figure 1 shows the details of the variation within 4 hr on the night of April 25.

Although the errors are relatively large on the nights of March 5 and April 28 because of the relatively poor weather, the presence of INOV can still be identified from the observations.

When we do aperture photometry, there is a problem regarding whether the contamination from the host galaxy of the target AGN contributes to the light variability. Some authors argued that the fluctuations in the seeing may result in spurious variable contributions from the host galaxy within the photometric aperture, especially when the apertures are small (Cellone et al. 2000). We argue that the contamination from the host galaxy is not important in the current study. First of all, no clear features of the host galaxy could be identified from the images taken by SDSS, likely because the object is far away from us (at  $z \approx 0.585$ ). Thus, the host galaxy is much fainter than the AGN. Second, as described above, the photometry apertures we adopted in this study are twice of the FWHM of field stars, which is large enough to include most of the emission from the underlying host galaxy.

#### 4. CONCLUSIONS AND DISCUSSION

The particular RL-NLS1 galaxy SDSS J094857.3+002225 was monitored in optical bands by NAOC 80 cm TNT telescope to search for its INOV phenomenon. Our optical monitoring indeed provides clear evidence for the presence of INOV in both the *B* and *R* bands in the object. The object exhibits optical variability not only on the timescale of a week, but also on several hours. The detection of the INOV indicates that the object contains a relativistic jet on the line of sight of an observer, which confirms the conclusion drawn from the high-energy observations (e.g., Abdo et al. 2009a, 2009b) and from the inverted radio spectrum and high brightness temperature (Zhou et al. 2003).

SDSS J094857.3+002225 is particular for its observational properties. On the one hand, its optical spectrum with strong Fe II emission is typical of NLS1s. The narrow H $\beta$  emission yields a relatively low black hole (BH) mass  $\sim 4.0 \times 10^7 M_\odot$  and a high Eddington ratio (Zhou et al. 2003). On the other hand, some observational behaviors are characteristic of blazars with the relativistic jets close to the line of sight, such as the INOV detected here, flat radio spectrum, high brightness temperature, and variable  $\gamma$ -ray emission (see citations in Section 1).

So far, outstanding RL-NLS1s with blazer-like radio emission have been revealed by multi-wavelength observations in several cases including the object SDSS J094857.3+002225. We refer the reader to Yuan et al. (2008) for a brief summarization. With the successful launch of *Fermi* satellite,  $\gamma$ -ray emission was detected in four RL-NLS1s, including the object studied here, which suggests the presence of fully developed jets in these objects (Abdo et al. 2009c). The authors argued that the four RL-NLS1s may form a new class of  $\gamma$ -ray AGNs because of their small BH masses, large Eddington ratios, and possibly disk-like morphology of the host galaxies.

The intrinsic mechanism of RL-NLS1s is an attractive field. There are two possible models for interpreting RL-NLS1s. The first one is the inclination model (Osterbrock & Pogge 1985; Komossa et al. 2006; Whalen et al. 2006; Komossa 2008). The model suspects that (at least a fraction of) the RL-NLS1s

are preferentially viewed pole-on. The observed narrow width of the Balmer emission lines could be resulted from small inclination if the broad-line region (BLR) is constrained to a plane (Wills & Browne 1986; Bian & Zhao 2004). In fact, there is some evidence supporting a flat BLR in some RL-AGNs (Jarvis & McLure 2006; Sulentic et al. 2003). In this scenario, the BH mass is largely underestimated in these objects since the current available estimation of the BH mass of AGN from single-epoch spectroscopic observation comes from an assumption of an isotropic distribution of the broad-line clouds with random orbital inclinations (Kaspi et al. 2005; Peterson et al. 2004; Bentz et al. 2007). Although the inclination model sounds reasonable because it is able to shift the location of RL-NLS1s on the  $R$ – $M_{\text{BH}}$  plane to the massive BH end (Laor 2000; Lacy et al. 2001), the massive BHs are not supported by the lack of massive bulges in several cases in which the host galaxies can be resolved.

The second is the accretion mode model (Komossa et al. 2006; Whalen et al. 2006; Komossa 2008). The RL-NLS1s with small BH masses are accreting close to or even above the Eddington limit. Low-mass BHs may lead to narrow emission lines when Keplerian velocities are considered mostly (Whalen et al. 2006). The accretion is thought to be related to the radio emission. Different accretion modes may result in different phenomena and maybe can explain the differences in the radio loudness. Accretion processes are known to be related to the spin of the accreting BHs. So the rapid spin of BHs may also affect the radio loudness of NLS1s (Komossa et al. 2006). It is possible that accretion mode combining with BH spin can explain the nature of the RL-NLS1s.

Although our monitor indicates that the extremely high radio emission in RL-NLS1 SDSS J094857.3+002225 is mainly contributed from the beamed non-thermal jet with a small viewing angle (can also be found in the aforementioned other studies), more information is needed in the future to investigate the origin of the relativistic jet.

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#### REFERENCES

- Abdo, A. A., et al. 2009a, *ApJ*, **699**, 976
- Abdo, A. A., et al. 2009b, *ApJ*, **707**, 727
- Abdo, A. A., et al. 2009c, *ApJ*, **707**, L142
- Bentz, M. C., et al. 2007, *ApJ*, **662**, 205
- Bian, W., & Zhao, Y. 2004, *MNRAS*, **352**, 823
- Boller, T. 1997, *Astron. Nachr.*, **318**, 209
- Boller, T., Brandt, W. N., & Fink, H. 1996, *A&A*, **305**, 53
- Cellone, S. A., Romero, G. E., & Combi, J. A. 2000, *AJ*, **119**, 1534
- Foschini, L., Maraschi, L., Tavecchio, F., Ghisellini, G., Gliozzi, M., & Sambruna, R. M. 2009, *Adv. Space Res.*, **43**, 889
- Healey, S. E., Romani, R. W., Taylor, G. B., Sadler, E. M., Ricci, R., Murphy, T., Ulvestad, J. S., & Winn, J. N. 2007, *ApJS*, **171**, 61
- Jarvis, M. J., & McLure, R. J. 2006, *MNRAS*, **369**, 182
- Kaspi, S., Maoz, D., Netzer, H., Peterson, B. M., Vestergaard, M., & Jannuzi, B. T. 2005, *ApJ*, **629**, 61
- Kellermann, K. I., Sramek, R., Schmidt, M., Shaffer, D. B., & Green, R. 1989, *AJ*, **98**, 1195
- Komossa, S. 2008, *RevMexAA Conf. Ser.*, **32**, 86
- Komossa, S., Voges, W., Xu, D., Mathur, S., Adorf, H. M., Lemson, G., Duschl, W., & Grupe, D. 2006, *AJ*, **132**, 531
- Lacy, M., Laurent-Muehleisen, S. A., Ridgway, S. E., Becker, R. H., & White, R. L. 2001, *ApJ*, **551**, L17

- Laor, A. 2000, [ApJ](#), **543**, L111
- Osterbrock, D. E., & Pogge, R. W. 1985, [ApJ](#), **297**, 166
- Peterson, B. M., et al. 2004, [ApJ](#), **613**, 682
- Pogge, R. W. 2000, [New Astron. Rev.](#), **44**, 381
- Sulentic, J. W., Zamfir, S., Marziani, P., Bachev, R., Calvani, M., & Dultzin-Hacyan, D. 2003, [ApJ](#), **597**, L17
- Sulentic, J. W., Zwitter, T., Marziani, P., & Dultzin-Hacyan, D. 2000, [ApJ](#), **536**, L5
- Wagner, S. J., & Witzel, A. 1995, [ARA&A](#), **33**, 163
- Whalen, D. J., Laurent-Muehleisen, S. A., Moran, E. C., & Becker, R. H. 2006, [AJ](#), **131**, 1948
- Wills, B. J., & Browne, I. W. A. 1986, [ApJ](#), **302**, 56
- Yuan, W., Zhou, H. Y., Komossa, S., Dong, X. B., Wang, T. G., Lu, H. L., & Bai, J. M. 2008, [ApJ](#), **685**, 801
- Zhou, H. Y., Wang, T. G., Dong, X. B., Zhou, Y. Y., & Li, C. 2003, [ApJ](#), **584**, 147