ON THE HOST GALAXY OF GRB 150101B AND THE ASSOCIATED ACTIVE GALACTIC NUCLEUS

CHEN XIE$^1$, TAOTAO FANG$^{2,3,5}$, JUNFENG WANG$^{2,3}$, TONG LIU$^{2,3,4}$, AND XIAOCHUAN JIANG$^2$

$^1$Department of Physics, Xiamen University, Xiamen, China
$^2$Department of Astronomy and Institute of Theoretical Physics and Astrophysics, Xiamen University, Xiamen, China; fangt@xmu.edu.cn
$^3$SHAO-XMU Joint Center for Astrophysics, Xiamen, China
$^4$Department of Physics and Astronomy, University of Nevada, Las Vegas, NV 89154, USA

Received 2016 May 22; revised 2016 May 30; accepted 2016 June 1; published 2016 June 13

ABSTRACT

We present a multi-wavelength analysis of the host galaxy of short-duration gamma-ray burst (GRB) 150101B. Follow-up optical and X-ray observations suggested that the host galaxy, 2MASX J12320498-1056010, likely harbors low-luminosity active galactic nuclei (AGNs). Our modeling of the spectral energy distribution has confirmed the nature of the AGN, making it the first reported GRB host that contains an AGN. We have also found the host galaxy is a massive elliptical galaxy with stellar population of $\sim5.7$ Gyr, one of the oldest among the short-duration GRB hosts. Our analysis suggests that the host galaxy can be classified as an X-ray bright, optically normal galaxy, and the central AGN is likely dominated by a radiatively inefficient accretion flow. Our work explores an interesting connection that may exist between GRB and AGN activities of the host galaxy, which can help in understanding the host environment of the GRB events and the roles of AGN feedback.

Key words: galaxies: active – galaxies: elliptical and lenticular, cD – gamma-ray burst: individual (GRB 150101B)

1. INTRODUCTION

Gamma-ray bursts (GRBs) are transient events that can be divided into two classes, short-duration ($<$2 s) and long-duration ($>$2 s) (Kouveliotou et al. 1993), or Type I and II GRBs (Zhang 2006; Zhang et al. 2009). The physical origins of the two classes are different: long GRBs (LGRBs) are triggered by the collapse of low-metallicity, massive stars (Woosley 1993; Woosley & Bloom 2006), and short GRBs (SGRBs) are thought to be originated from mergers of compact binary systems, such as a black hole and a neutron star (BH--NS), or two neutron stars (NS--NS; Eichler et al. 1989; Paczyński 1991; Narayan et al. 1992).

The environments of the GRB host galaxies provide important clues for understanding these energetic cosmic events and have been under intensive study over the past two decades (see, e.g., Gehrels et al. 2009 and Berger 2014 for reviews). In general, long-duration bursts are associated with star-forming galaxies (Le Floc’h et al. 2006; Chary et al. 2007; Fynbo et al. 2008; Savaglio et al. 2009) that can be either faint or bright (Perley et al. 2016a, 2016b). On the other hand, the short-duration bursts typically have long-lived progenitors, and their host galaxies show a mixed population of early- and late-type galaxies, with a wide span of star formation rates (Gehrels et al. 2009; Berger 2014).

Up until GRB 150101B, neither long- nor short-duration GRB hosts show activities of active galactic nuclei (AGNs) in the center. Due to the link between the long-duration bursts and the core collapse of massive stars, it was suspected that some GRB hosts with bright submillimeter or infrared emission may be powered by AGNs (see, e.g., Tanvir et al. 2004; Gehrels et al. 2009; Stanway et al. 2015). Several attempts have been made to identify AGNs in the GRB hosts, but have yielded no results (Fruchter 2005; Predel 2011; Sytznovidis 2012). Yet, it remains extremely interesting to explore the connection between GRBs and the star formation and AGN activities of the host galaxies, as it may provide important clues about the role of AGN feedback, as well as the GRB host environment.

In this Letter, we present a multi-wavelength analysis of the host galaxy of GRB 150101B. We confirm this host galaxy contains a central AGN, which was first suggested by Levan et al. (2015b), Fong et al. (2015b), and Troja et al. (2015). To date, it is the first confirmed AGN in a known GRB host population. We also suggest that the host galaxy can be classified as an X-ray bright, optically normal galaxy (XBONG; Moran et al. 1996; Yuan & Narayanan 2004; Brandt & Hasinger 2005). Observations and data analysis are presented in Section 2. In Section 3, we fit the host spectral energy distribution (SED) and discuss the nature of the host galaxy and central AGN. Section 4 is a discussion and summary. Throughout the Letter, we adopt the standard $\Lambda$CDM cosmology with $\Omega_M = 0.30$, $\Omega_{\Lambda} = 0.70$, and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$.

2. MULTI-WAVELENGTH OBSERVATIONS OF GRB 150101B AND ITS HOST GALAXY

2.1. γ-Ray and Optical

Swift Burst Alert Telescope (BAT) was triggered by GRB 150101B at 15:23 UT on 2015 January 1. The light curve shows a single peak with a duration ($T_{90}$) of 0.018 ± 0.006 s (Cummings 2015). Fermi was also triggered with a duration ($T_{90}$) of about 0.08 s (50–300 keV; Stanbro 2015). At $\sim3^{\circ}$ away, the Very Large Telescope (VLT) clearly detected the optical emission from the bright galaxy, 2MASX J12320498-1056010, which was identified as the host galaxy of GRB 150101B (Levan et al. 2015b). The VLT spectra show several prominent absorption features, most notably Mg b and Na D, at a redshift of 0.134 (Levan et al. 2015b). The Gran Telescopio CANARIAS (GTC) also detected a faint, single emission line, which they tentatively identified as an [O III] emission line at $z \sim 0.093$ (Castro-Tirado et al. 2015). However, the GTC data suffered from poor weather conditions, passing clouds, and bad seeing ($>$2.5'); Castro-Tirado et al. 2015). Therefore, we adopt $z = 0.134$ as the redshift of the host galaxy in this work. This is
one of the lowest redshifts among SGRB hosts (Fong et al. 2015a). The estimated GRB isotropic energy between 15 and 150 keV is $9.7 \times 10^{47}$ erg at $z = 0.134$.

### 2.2. X-Ray Observations

Two *Chandra* follow-up observations were performed at 7.8 days (Troja et al. 2015) and 39 days (Levan et al. 2015a) after the burst, respectively. In Figure 1, the images taken by the two *Chandra* observations show a bright and a fading source. The position of the fading X-ray counterpart is consistent with the only fading optical source in the BAT position, reported by Fong et al. (2015a).

The X-ray data reduction was performed with the *Chandra* Interactive Analysis of Observations (CIAO) software package\(^5\) (version 4.6). The spectra extracting region is shown in Figure 1 in blue circles. For the X-ray fading counterpart, the net count rates of the first and second epoch are $(9.6 \pm 0.8)$ and $(1.4 \pm 0.3) \times 10^{-3}$ cts s\(^{-1}\), respectively. Therefore, the fading X-ray source is identified as the GRB afterglow.

The position of the bright source is located in the nucleus of the known galaxy 2MASX J12320498-1056010, which was reported by several surveys and follow-up observations (see Table 1 for photometry). Adopting the images from the two *Chandra* observations, the bright source coordinate is (R.A., decl.) = ($12^h32^m04^s965$, $-10^d56^m00^s59$) and the fading source coordinate is (R.A., decl.) = ($12^h32^m05^s099$, $-10^d56^m02^s55$), with a 90% uncertainty of 0\(^\circ\).6. The offset between two sources is $\sim2\arcsec 77$, and the projected physical offset is 6.61 kpc at $z = 0.134$. About 35% of SGRBs are located at more than 7 kpc away from the center of the host galaxies (see Figure 10 in Berger 2014). Furthermore, the host light extends beyond the position of the GRB optical afterglow (Levan et al. 2015b). The possibility of such a bright source coincidentally appearing in the region of GRB in a radius of $10\arcsec$ is less than $2.4 \times 10^{-4}$ (Manners et al. 2003). Therefore, we conclude that the bright X-ray source is the nucleus of the host galaxy 2MASX J12320498-1056010.

---

**Figure 1.** Two *Chandra* observations. The first epoch (Troja et al. 2015) began on 2015 January 9 (7.83 days post-burst) for an exposure time of 14.87 ks. The second epoch (Levan et al. 2015a) began on 2015 February 10 (39 days post-burst and 32 days after the first epoch) for an exposure time of 14.86 ks. Comparing the two epochs, we can clearly see the fading afterglow counterpart. AGN (bright and marked by green circles) and afterglow (faint and marked by blue circles) positions are consistent with the host nucleus and GRB optical afterglow, respectively. The circled areas are the regions where we extract the spectra of the AGN and GRB.

---

**Table 1**

| Band | $\lambda_{\text{eff}}$ | Instrument | Flux (mJy)\(^a\) |
|------|------------------|------------|------------------|
| FUV  | 1528 Å            | *GALEX*    | 0.013 ± 0.005    |
| NUV  | 2271 Å            | *GALEX*    | 0.012 ± 0.003    |
| UVM2 | 2310 Å            | XMM OM     | <0.013\(^b\)    |
| UVW1 | 2910 Å            | XMM OM     | <0.022\(^b\)    |
| U   | 3440 Å            | XMM OM     | <0.046\(^b\)    |
| V   | 5430 Å            | XMM OM     | <0.636\(^b\)    |
| J   | 1.24 μm           | 2MASS      | 1.120 ± 0.090    |
| H   | 1.66 μm           | 2MASS      | 1.444 ± 0.144    |
| Ks  | 2.16 μm           | 2MASS      | 1.603 ± 0.130    |
| W1  | 3.4 μm            | *WISE*     | 1.306 ± 0.032    |
| W2  | 4.6 μm            | *WISE*     | 0.917 ± 0.025    |
| W3  | 12 μm             | *WISE*     | 0.323 ± 0.145    |
| W4  | 22 μm             | *WISE*     | <2.553\(^d\)    |
| 9.8 GHz | 3 cm              | VLA        | 3.15 ± 0.02     |
| 4.9 GHz | 6 cm              | WSRT       | 7.21 ± 0.07     |
| 1.4 GHz | 20 cm             | VLA        | 10.2 ± 1.0     |

**Notes.**

\(^a\) Fluxes have been corrected for Galactic extinction (except radio fluxes) where $A_v = 0.1096$.

\(^b\) Errors are quoted at the 1\(\sigma\) level unless otherwise specified.

\(^c\) Data taken from *XMM-Newton* OM were adopted as upper limits since OM cannot separate the GRB and the host.

\(^d\) Corresponds to 95% upper limit.

To increase the photon statistics, we merged the two observations of the bright source and extract its X-ray spectrum for modeling (green regions in Figure 1). We used the XSPEC package v12.8.2 and adopted a model of the power law with two photoelectric absorptions. One photoelectric absorption was fixed at the Galactic value\(^7\) of $N(H) = 3.24 \times 10^{20}$ cm\(^{-2}\), and one was let free at the redshift of the host galaxy. This simple model provides an adequate fit to the X-ray spectrum. The fitted $N(H)$ at the redshift of the host galaxy is $3 \times 10^{19}$ cm\(^{-2}\), and the power-law index is 2.2 ± 0.1. We have derived a flux of $2.86 \times 10^{-13}$ erg cm\(^{-2}\) s\(^{-1}\) in

---

\(^5\) [http://asc.harvard.edu/ciao/](http://asc.harvard.edu/ciao/)

\(^6\) [http://asc.harvard.edu/toolkit/colden.jsp](http://asc.harvard.edu/toolkit/colden.jsp)
0.5–8.0 keV and a luminosity of $1.37 \times 10^{43}$ erg s$^{-1}$ in 0.5–8.0 keV. As we will discuss later in this Letter, the source X-ray luminosity indicates it is a low-luminosity AGN, and this AGN showed no variation during the two epochs (32 days). Our flux is somewhat lower than that of Troja et al. (2015), which may be attributed to the size of the source extraction region.

Note that the XMM-Newton also have ~30 ks observation for this source after the burst proposed by Campana (2015). But the GRB and the central AGN cannot be spatial resolved.

### 2.3. Other Observations

Table 1 lists multi-wavelength observations of 2MASX J12320498-1056010, the host galaxy of GRB 150101B. Column 1 shows the observing bands from UV to radio. Column 2 shows the effective wavelength of each band. Column 3 shows the instruments with which the observation was taken at each band. Column 4 shows the host fluxes after Galactic extinction correction (except radio fluxes) where $A_v = 0.1096$ (Cardelli et al. 1989; Robotham & Driver 2011; Schlafly & Finkbeiner 2011). The Galaxy Evolution Explorer (GALEX) has detected the host, namely, GALEX J123205.0-105600, at a distance of 0.06 from the center of 2MASX J12320498-1056010. The optical/UV telescope (OM) on board XMM-Newton and Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010) has also detected the host at a distance of 2.7 and 0.64, respectively. The radio continua at 9.8 and 4.9 GHz are adopted from Fong (2015) and van der Horst et al. (2015). The 1.4 GHz flux is taken from the NRAO VLA Sky Survey (Condon et al. 1998).

### 3. THE HOST GALAXY OF GRB 150101B

#### 3.1. SED Fitting and the Host Galaxy

Using all the available photometric data presented in Table 1, we have fitted the SEDs of the host galaxy with the Code Investigating GALaxy Emission (CIGALE; Noll et al. 2009). We have also included an AGN component (Fritz et al. 2006). In Figure 2, we present the data points and the model continuum. The fit is reasonably good with a $\chi^2$/dof of 9.6/11.

### 3.2. AGN

The most unique property is the detection of a central AGN in the host galaxy of GRB 150101B, first suggested by Levan et al. (2015b), Fong et al. (2015b), and Troja et al. (2015). Our multi-waveband analysis has confirmed the existence of the AGN, which makes it the first GRB host with a reported AGN. Besides the clear detection of an X-ray point source in the center of the host galaxy, we draw the conclusion based on the following findings. First, our SED fitting required an AGN component (green line in Figure 2). We have experimented with the fit of a model without the AGN component and have found such a fit officially unacceptable ($\chi^2$/dof = 1.54). The main problem with such a model is that it cannot fit the high flux presented in the UV band observed with GALEX.

Second, the observed X-ray and mid-infrared luminosities are consistent with the intrinsic correlation among AGNs discovered by Mullaney et al. (2011). The observed X-ray luminosity between 2 and 10 keV is $L_X = 7.46 \times 10^{42}$ erg s$^{-1}$, and the predicted mid-infrared flux at 12 $\mu$m is between 0.3 and 4 mJy. This is consistent with the WISE3 data of 0.323 ± 0.145 mJy and suggests that the galaxy emission in mid-IR is dominated by the central AGN. Finally, the SED modeling also shows a synchrotron emission with a spectral slope of $-0.62 \pm 0.03$ in the radio band, suggesting AGN-related activities.

Our SED fitting also suggest this is a radio-loud AGN. Conventionally, the radio loudness (Netzer 2013) is defined as

$$R = L_v(5 \text{ GHz})/L_v(4400 \text{ Å}).$$

Using a B-band flux of 0.099 mJy from our SED model, we have found a radio loudness of $R \approx 73$. Both the radio loudness and the spectral index in the radio band suggest this AGN is not...
a type I AGN. This conclusion is also supported by the derived angle between equatorial axis and line of sight (48° ± 9°) from the SED fitting.

Very interestingly, all the properties of the host galaxy of GRB 150101B suggest it belongs to a special class of galaxies, namely, the X-ray bright, optically normal galaxies (XBONGs; see, e.g., Moran et al. 1996; Yuan & Narayan 2004; Brandt & Hasinger 2005). The observed X-ray luminosity of the host galaxy is consistent with those typical of XBONGs in the range of $10^{41}-10^{43}$ erg s$^{-1}$. The observed X-ray to optical flux ratio of $X/O \approx -1.1$ is also consistent with those of XBONGs ($X/O \approx -1$). Such a flux ratio in general indicates some moderate level of AGN activities. Finally, the lack of optical emission features of those typical of AGNs is also consistent with the definition of XBONGs.

Brandt & Hasinger (2005) suggested three scenarios that may explain XBONGs: AGNs with heavy obscuration, BL Lac-like objects, or AGNs with radiatively inefficient accretion flow (RIAF; Yuan & Narayan 2004). In the host galaxy of GRB 150101B, the observed low $\alpha$, and moderate X-ray luminosity suggest that the first two scenarios are unlikely. For the central AGN we discussed here, the observed optical-to-X-ray spectral index is $\alpha_{OX} = 1.15$ (2500 Å–2 keV). Adopting the $M_{BH} = M_{\text{host}}$ relation in Sherman et al. (2014), we estimate the $M_{BH} = 10^{8.4} M_{\odot}$ and an Eddington ratio of $\sim 4.4 \times 10^{-3}$. Those values, as well as the radio loudness, are consistent with the predictions of the RIAF model (Yuan & Narayan 2004, 2014). Therefore, we conclude that the central AGN of the host galaxy is dominated by RIAF.

4. DISCUSSIONS AND CONCLUSIONS

In this Letter, we present a multi-wavelength analysis of the host galaxy of GRB 150101B. We have confirmed the host galaxy harbors an AGN, based on: (1) the X-ray detection of a central point source with high X-ray luminosity; (2) broadband SED modeling; (3) the correlation between observed X-ray and mid-infrared luminosities; and (4) the radio loudness and radio spectral index. We also found the host galaxy belongs to a special class of galaxies, the XBONGs. The observed properties of this AGN are consistent with being dominated by an RIAF.

GRB 150101B is the first confirmed GRB–AGN system. To date, no AGN was detected among LGRB hosts, and only one is reported among SGRB hosts (this work). It is still unclear why the GRB host galaxies show very little or no AGN activities. AGNs are rare among galaxies, so one reason might simply be due to counting statistics. The fraction of high-ionization AGNs in local galaxies is about 2% (the fraction of low-ionization AGNs is larger; Netzer 2013). This rate becomes higher at high redshift when AGN activities peak between redshift 2 and 3. To date, redshift measurements have been reported for a total of $\sim 450$ GRBs; however, some of these measurements were performed on the GRB afterglows and not on the host galaxies. Adopting a conservative number of $\sim 200$ GRB host galaxies from the GHostS sample, we would expect roughly 4 galaxies with AGN activities if AGNs and GRBs are independent phenomena. So it probably is not entirely a surprise if we only observed one. Future multi-wavelength study of the GRB host galaxies should be able to resolve this issue.

On the other hand, if AGNs do become less likely to be detected among the GRB hosts, one possibility is that AGN activities quench the star formation in the host galaxies, therefore reducing the likelihood of detecting LGRB events in such an environment. However, since SGRB hosts typically show a wide span of stellar population ages, they clearly exhibit a link with the delayed star formation activities (Berger 2014). Therefore, it is likely to detect some level of AGN activities among SGRB hosts. In particular, we have found that the host galaxy of GRB 150101B belongs to XBONGs, suggesting the direction of further study of the link between AGN activities and GRBs.

We thank Dr. Denis Burgarella for answering our questions about CIGALE. We also thank Drs. Weimin Gu, Mouyun Sun, Tinggui Wang, Feng Yuan, and Bing Zhang for beneficial discussion. This work was supported by the National Basic Research Program of China (973 Program) under grant 2014CB845800, by the National Natural Science Foundation of China under grants 11233006, 11273021, 11473021, 11473022, 11523230, 11552312, and U1331101, by the Fundamental Research Funds for the Central Universities under grants 20720160023, 20720160024, and 2013121008, and by the Strategic Priority Research Program “The Emergence of Cosmological Structures” of the Chinese Academy of Sciences, grant No. XDB09000000. The FAST FELLOWSHIP is supported by Special Funding for Advanced Users, budgeted and administrated by Center for Astronomical Mega-Science, Chinese Academy of Sciences (CAMS).

This research has made use of data obtained from the Chandra Data Archive and the Chandra Source Catalog, and software provided by the Chandra X-ray Center (CXC) in the application packages CIAO. This publication makes use of data products from the Two Micron All Sky Survey (Skrutskie et al. 2006), which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation. Based in part on public data from GALEX GR6/GR7. The Galaxy Evolution Explorer (GALEX) satellite is a NASA mission led by the California Institute of Technology. This publication makes use of data products from the Wide-field Infrared Survey Explorer (Wright et al. 2010), which is a joint project of the University of California, Los Angeles, and the Jet Propulsion Laboratory/California Institute of Technology, funded by the National Aeronautics and Space Administration. This research has made use of the GHostS database (www.grbhosts.org), which is partly funded by Spitzer/NASA grant RSA Agreement No. 1287913.

REFERENCES

Berger, E. 2014, ARA&A, 52, 43
Brandt, W. N., & Hasinger, G. 2005, ARA&A, 43, 827
Campana, S. 2015, GCN, 17318, 1
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Castro-Tirado, A. J., Sanchez-Ramirez, R., Gorosabel, J., & Scarpa, R. 2015, GCN, 17278, 1
Chary, R., Berger, E., & Cowie, L. 2007, ApJ, 671, 272
Condon, J. J., Cotton, W. D., Greisen, E. W., et al. 1998, AJ, 115, 1693
Cummings, J. R. 2015, GCN, 17267, 1

http://www.astro.caltech.edu/grbox/grbox.php
http://www.grbhosts.org
