HOST GALAXY PROPERTIES AND BLACK HOLE MASS OF SWIFT J164449.3+573451 FROM MULTI-WAVELENGTH LONG-TERM MONITORING AND HST DATA

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Received 2015 April 28; accepted 2015 June 18; published 2015 July 23

ABSTRACT

We study the host galaxy properties of the tidal disruption object Swift J164449.3+573451 using long-term optical to near-infrared (NIR) data. First, we decompose the galaxy surface brightness distribution and analyze the morphology of the host galaxy using high-resolution Hubble Space Telescope WFC3 images. We conclude that the host galaxy is bulge-dominant and well described by a single Sérsic model with Sérsic index $n = 3.43 ± 0.05$. Adding a disk component, the bulge to total host galaxy flux ratio $(B/T)$ is $0.83 ± 0.03$, which still indicates a bulge-dominant galaxy. Second, we estimate multi-band fluxes of the host galaxy through long-term light curves. Our long-term NIR light curves reveal the pure host galaxy fluxes ~500 days after the burst. We fit spectral energy distribution models to the multi-band fluxes from the optical to NIR of the host galaxy and determine its properties. The stellar mass, the star formation rate, and the age of the stellar population are $\log(M/\odot) = 9.14^{+0.13}_{-0.10}$, $0.03^{+0.08}_{-0.05} M_\odot$ yr$^{-1}$, and $0.63^{+0.95}_{-0.43}$ Gyr. Finally, we estimate the mass of the central super massive black hole which is responsible for the tidal disruption event. The black hole mass is estimated to be $10^{6.7^{+0.4}_{-0.3}} M_\odot$ from $L_{BH}=M_{BH, bul}$ and $M_{BH}/L_B^K$ relations for the $K$ band, although a smaller value of $\sim 10^5 M_\odot$ cannot be excluded convincingly if the host galaxy harbors a pseudobulge.

Key words: galaxies: active – galaxies: nuclei – galaxies: photometry – galaxies: structure – techniques: photometric

1. INTRODUCTION

Swift J164449.3+573451 (hereafter, Swift J1644+57) was first discovered by the Swift Burst Alert Telescope (BAT) at 12:57:45 UT on 2011 March 28 (Burrows et al. 2011; Levan et al. 2011). Some evidence suggests that Swift J1644+57 is the tidal disruption of a star by a supermassive black hole (SMBH). This phenomenon triggered the BAT three times after the initial trigger during the first few days (Burrows et al. 2011; Levan et al. 2011). The late-time X-ray light curve was extended to a longer period by following the expected power-law decay for the tidal disruption of a star, i.e., $t^{-5/3}$ (e.g., Rees 1988). Finally, the sources of the X-ray, IR, and radio emissions were well matched with the center of the host galaxy where a SMBH resides (Levan et al. 2011; Zauderer et al. 2011).

There have been many studies performed to understand the nature of this event, such as the characteristics of the star that was disrupted. Such a question is closely connected to the SMBH mass ($M_{BH}$). The disruption of a solar-type star is possible for all $M_{BH} < 10^5 M_\odot$ (Rees 1988; Cannizzo et al. 1990; Bloom et al. 2011), but compact stars like a white dwarf can be disrupted only if $M_{BH} < 10^3 M_\odot$ (Krolik & Piran 2011). If so, then this type of event provides the interesting possibility of discovering intermediate-mass black holes.

Unfortunately, there has been controversy concerning the mass of the SMBH. Burrows et al. (2011) provided a rough estimate of the SMBH mass of $\sim 2 \times 10^5 M_\odot$ using a black hole mass–luminosity relation and a lower limit of $\sim 10^6 M_\odot$ based on the X-ray variability. Similarly, Levan et al. (2011) estimated the $M_{BH}$ to be $2 \times 10^6-10^7 M_\odot$, derived from the $K$-band luminosity, but at that time the $K$-band luminosity contained a significant amount of the transient light. Miller & Gultekin (2011) utilized a relation between the black hole mass, the radio luminosity, and the X-ray luminosity, and found $M_{BH} \sim 10^{5.5} M_\odot$. Using a quasi-periodic oscillation resonance hypothesis, Abramowicz & Liu (2011) provided an $M_{BH}$ estimate of $\sim 10^5 M_\odot$. Krolik & Piran (2011) concluded that a white dwarf was tidally disrupted and the mass of the SMBH is less than $10^5 M_\odot$ in light of the short timescales of the X-ray light curve. In summary, the $M_{BH}$ estimates have centered around the two discrepant values of $10^5 M_\odot$ and $10^6 M_\odot$ or less. A better understanding of the host galaxy properties is needed to clear up the situation.

In order to more accurately estimate the SMBH mass and better constrain the properties of the host galaxy, we analyze the morphology and surface brightness profile of the host galaxy based on high-resolution Hubble Space Telescope (HST) images and estimate the multi-band fluxes of the host galaxy using our long-term monitoring data lasting more than...
2.4 years. We fit the multi-band spectral energy distribution (SED) of the host galaxy luminosity with stellar population synthesis models, and then obtain the properties of the galaxy. Finally, we provide our best estimate of $M_{\text{BH}}$ based on the host galaxy properties.

This is the second in a series of two papers. In the first paper (M. Im et al. 2015, in preparation, hereafter, Im15), we present the data set of the long-term monitoring campaign and an analysis of the late-time light curve.

Throughout the paper, we selected $H_0 = 70 \, \text{km s}^{-1} \, \text{Mpc}^{-1}$, $\Omega_{\Lambda} = 0.7$, and $\Omega_{\text{m}} = 0.3$ as cosmological parameters and adopt the AB magnitude system.

### 2. OBSERVATIONS AND DATA

We observed Swift J1644+57 using the Wide Field Camera (WFCAM) on UKIRT for nearly 2.4 years following the burst as a part of our gamma-ray burst and transient observation program (Lee et al. 2010). We observed intensively in the $K$ band using the $Z$, $Y$, $J$, $H$, and $K$ bands of WFCAM. The number of epochs of $K$-band data used for the analysis is 101 and the last data were observed 884.7 days after the initial BAT trigger. The numbers of epochs for the $Y$, $J$, $H$-band data are 3, 15, 28, and the last data were observed at $\Delta t = 712.1$, 710.1, and 884.7 days, respectively, where $\Delta t$ is the number days since the initial BAT trigger. We have only one epoch of data for the UKIRT $Z$ band which was observed at $\Delta t = 723.0$ days.

We also observed Swift J1644+57 using the Camera for QUasars in EArly uNiverse (CQUEAN; Kim et al. 2011; Park et al. 2012; Lim et al. 2013) on the 2.1 m Otto-Struve telescope of the McDonald Observatory in the $g$, $r$, $i$, $z$, and $Y$ bands. The numbers of epochs for the $g$, $r$, $i$, $z$, and $Y$ data are 2, 2, 14, 14, and 2, and the last data were observed at $\Delta t = 25.7$, 217.5, 526.6, 526.6, and 25.8 days respectively. The UKIRT and CQUEAN observation logs and photometry results are described in Im15.

In addition, we also used data from Burrows et al. (2011) and Levan et al. (2011) for the earlier optical and near-infrared (NIR) data. Morphology analysis requires high-resolution images because this object is so compact that it is virtually a point source in the UKIRT and CQUEAN images. For the high-resolution images, we obtained $HST$ WFC3 multi-drizzled, stacked images\(^8\) available in the MAST database. We used the $F606W$- and $F160W$-band data and the number of epochs in each two band is four. These data were observed at $\Delta t = 6.6, 129, 249,$ and 746 days. The $HST$ WFC3 data are summarized in Table 1.

To supplement the NIR observation data, we used the $Spitzer$ IRAC 3.6, 4.5 $\mu$m post-basic calibrated data from the NASA/IPAC Infrared Science Archive. These were observed at $\Delta t = 31.4, 216.5,$ and 333.0 days. A log of the $Spitzer$ IRAC 3.6, 4.5 $\mu$m data are shown in Table 2.

The flux measurements were performed by SExtractor software\(^9\) (Bertin & Arnouts 1996), except for the $HST$ images for which GALFIT (Peng et al. 2010) models were used for the flux measurements.

\(^{8}\) Based on observations made with the NASA/ESA Hubble Space Telescope, obtained from the data archive at the Space Telescope Science Institute. STScI is operated by the Association of Universities for Research in Astronomy, Inc. under NASA contract NAS 5-26555.

\(^{9}\) We used aperture magnitudes with aperture correction.

### Table 1

| Observation Date (UT) | MJD\(^a\) | Days Since Trigger | Band | Exptime (s) | Magnitude (AB) |
|----------------------|-----------|--------------------|------|-------------|----------------|
| 2011 Apr 04          | 55655.147614 | 6.6 | $F606W$ | 1260 | 22.69 ± 0.01 |
| 2011 Aug 04          | 55777.276876 | 129 | $F606W$ | 4160 | 22.76 ± 0.01 |
| 2011 Dec 02          | 55897.684390 | 249 | $F606W$ | 1113 | 22.77 ± 0.01 |
| 2013 Apr 12          | 56394.429204 | 746 | $F606W$ | 2600 | 22.74 ± 0.01 |
| 2011 Apr 04          | 55655.132654 | 6.6 | $F160W$ | 997  | 20.68 ± 0.01 |
| 2011 Aug 04          | 55777.257148 | 129 | $F160W$ | 1412 | 21.09 ± 0.01 |
| 2011 Dec 02          | 55897.702220 | 249 | $F160W$ | 1209 | 21.22 ± 0.02 |
| 2013 Apr 12          | 56394.295795 | 746 | $F160W$ | 2812 | 21.55 ± 0.02 |

\(^{a}\) Exposure start time in Modified Julian Date (MJD).

### Table 2

| Observation Date (UT) | MJD\(^a\) | Days Since Trigger | Band | Exptime (s) | Magnitude (AB) |
|----------------------|-----------|--------------------|------|-------------|----------------|
| 2011 Apr 28          | 55679.975316 | 31.4 | 3.6 $\mu$m | 1250 | 19.50 ± 0.02 |
| 2011 Oct 31          | 55865.023052 | 216 | 3.6 $\mu$m | 1253 | 21.49 ± 0.06 |
| 2012 Feb 24          | 55981.541644 | 333 | 3.6 $\mu$m | 1252 | 21.70 ± 0.07 |
| 2011 Apr 28          | 55679.975316 | 31.4 | 4.5 $\mu$m | 1250 | 19.30 ± 0.01 |
| 2011 Oct 31          | 55865.023052 | 216 | 4.5 $\mu$m | 1253 | 21.25 ± 0.05 |
| 2012 Feb 24          | 55981.541644 | 333 | 4.5 $\mu$m | 1252 | 21.57 ± 0.08 |

\(^{a}\) MJD in UTC at data collection event (DCE) start.
For the X-ray data, we used Swift/XRT data taken from the Swift archive and XMM-Newton data\(^\text{10}\) from the XMM-Newton Science Archive.

### 3. MORPHOLOGY OF THE HOST GALAXY

We analyzed the surface brightness profile of the host galaxy in order to determine the bulge fraction and its nature. We used the \textit{HST} images and GALFIT software to fit two-dimensional models to the light distribution of the host galaxy. To construct the point-spread function (PSF), we selected \(\sim 5\) isolated stars with signal-to-noise ratios \(\gtrsim 300\) in the vicinity of Swift J1644+57 and co-added them.

We used error images created by GALFIT for the fitting. For GALFIT to create the error image properly, we modified the unit of ADU and the image header values such that \(\text{GAIN} \times \text{ADU} \times \text{NCOMBINE} = \text{[electrons]}\) as recommended in the GALFIT website.\(^\text{11}\)

A crucial factor affecting the fitting results is background subtraction. For the background determination, we set 6 annuli with radii logarithmically increasing between 2.5 and 9 times the radius of an ellipse for which pixel values are 1.5\(\sigma\) of the background noise. We centered the annuli on the center of the host galaxy, set the minimum width of the annuli to be \(\sim 1.3\) arcsec (\(\sim 33\) pixel) for \(\text{F}0606\) images and \(\sim 2\) arcsec (\(\sim 16\) pixel) for \(\text{F}160W\) images, and augmented the widths in step with the logarithmically growing radii. We then derived the mean pixel values of each annulus. Finally, we adopted their mean value as the background value.

Our surface brightness fit was carried out using a deep, stacked image of the data taken with \(\text{F}0606\) at \(\Delta t = 129, 249,\) and 749 days. It has been known that the transient component is negligible in the optical bands bluer than \(i\) even at early times (Burrows et al. 2011; Levan et al. 2011). The use of the stacked, late-time image in the \(\text{F}0606\) band makes the transient component more negligible. On the other hand, NIR bands, including \(\text{F}160W\) (similar to \(H\) band of WFCAM), are known to contain a significant transient component which may affect the host galaxy analysis. Furthermore, the spatial resolution of the \(\text{F}0606\) images is better by a factor of three than that of \(\text{F}160W\), which greatly helps the surface brightness fitting. The other \(\text{HST}\) data were also analyzed to understand the importance of the transient component, and the results for the transient component are presented later in this section.

For the galaxy models, we used the Sérsic (1968), de Vaucouleurs (1948), and exponential disk profiles or a combination thereof. The Sérsic profile is described as:

\[
\Sigma(r) = \Sigma_e \exp \left( -\kappa \left( \frac{r}{r_e} \right)^{1/n} - 1 \right),
\]

where \(\Sigma_e\) is the surface brightness at the effective radius \(r_e\) and \(n\) is the Sérsic index. \(\kappa\) is a variable parameter dependent on \(n\), where \(n = 4\) and 1 correspond to the de Vaucouleurs and exponential profiles, respectively. Although \(n = 4\) is commonly quoted for the ellipticals and classical bulges, the Sérsic index of ellipticals and classical bulges can assume a value in the range \(2 \lesssim n \lesssim 6\), whereas pseudobulges have \(n \lesssim 2\) (Fisher & Drory 2008, 2010).

All of the model parameters, such as the ellipticity and center positions of the different components, were set free in the fitting procedure.

Figures 1 and 2 show images of the host galaxy, the two-dimensional models, and the residuals (i.e., the model subtracted images) for four different models: (1) a single Sérsic; (2) a Sérsic bulge + exponential disk; (3) an exponential disk; and (4) a double exponential profile model. The figures also show one-dimensional profiles (along the major axis) of the host galaxy and those of each model component, which are converted through the IRAF\(^\text{12}\) ELLIPSE task. In addition to the profiles, the differences between the data and the model profiles are shown. The results of each fit are summarized in Table 3. Both the single Sérsic model with \(n = 3.43 \pm 0.05\) and the Sérsic bulge with \(n = 3.39 \pm 0.11\) + exponential disk model fit the data well (\(\chi^2 \sim 1.2\)). When the disk component is added, the bulge to total host galaxy flux ratio \((B/T) = 0.83 \pm 0.03\). On the other hand, the single exponential disk model provides a poor fit to the data as shown in Figure 2 and with \(\chi^2 = 6.54\). The double exponential profile model fits the data nearly as well as the single Sérsic model and the Sérsic bulge + disk model in terms of \(\chi^2\). However, the analysis of the one-dimensional surface brightness profile shows that the model does not follow the outer part of the profile well, demonstrating a relatively steeper decline than that of the single Sérsic model and the Sérsic bulge + exponential disk model. This model gives \(B/T = 0.36\), suggesting a significant bulge component. Therefore, we conclude that the host galaxy of Swift J1644+57 is bulge-dominant. We also conclude that the bulge is likely to have a Sérsic index higher than three regardless of the existence of the disk. This value corresponds to the range of classical bulges (Fisher & Drory 2008, 2010). We cannot completely exclude the case where the bulge is a pseudobulge with \(n \sim 1\), but even in this case the object has a significant bulge.

Additionally, we fit the observed surface brightness profile with a single de Vaucouleurs bulge model and a de Vaucouleurs bulge + exponential disk model. The results of these fits are nearly identical to those of the single Sérsic and the Sérsic bulge+disk models.

To estimate the transient component flux, we fit all the \(\text{F}0606W\) and \(\text{F}160W\) images with a model containing both the point source (transient) and the host galaxy components. Here, we adopt a single Sérsic profile with a fixed Sérsic index \((n = 3.43)\) for the host galaxy component, and a PSF profile for the transient component. The compactness of the host galaxy and the bright transient component in the \(\text{F}160W\) images create a serious degeneracy, particularly between the effective radius and the Sérsic index, when fitting multi-component models. To alleviate the degeneracy, we fixed the Sérsic index to be \(n = 3.43\), similar to that of the \(\text{F}0606W\) band. The flux fractions of the models as a function of time are shown in Figure 3. In the case of \(\text{F}0606W\), the flux fraction from the transient component is very small or nonexistent, while the transient component is very bright in the earliest \(\text{F}160W\) band, even brighter than the entire host galaxy. The result reflects a very red color to the transient well, and

\(^{10}\) Based on observations obtained with \textit{XMM-Newton}, an ESA science mission with instruments and contributions directly funded by ESA Member States and NASA.

\(^{11}\) \url{http://users.obs.carnegiescience.edu/peng/work/galfit/TOP10.html}

\(^{12}\) IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under a cooperative agreement with the National Science Foundation.
justifies the exclusion of the point source component in the late-time $F606W$ images during the host galaxy analysis. The point source contribution declines rapidly as time goes on in $F160W$, but it contributes to the total flux of the object until around $\Delta t = 750$ days. On the other hand, the fluxes of the host galaxy component are almost constant in both bands over the entire period. The magnitude of the host galaxy in the $F160W$ band is $\sim 21.75$ mag, and as we shall see in the next section, this is the same as for the last data point of the UKIRT $H$-band light curve, suggesting that the flux of the last data point in the NIR light curve represents the host galaxy flux.

4. LIGHT CURVES

In this section, we show long-term observation results and estimate multi-band fluxes of the host galaxy of Swift J1644 +57. Figure 4 shows the $Y$, $J$, $H$, and $K$ light curves. The gray data points in the background show Swift/XRT 0.3–10 keV data. The $J$, $H$, $K$ light curves resemble each other. The NIR light curves rapidly decline until $\Delta t \approx 10$ days, turn up again
with a second peak at $\Delta t \approx 30 \text{ days}$, and decline again steadily. The behaviors of these NIR light curves are very similar to that of the X-ray light curve, except that the X-ray light curve appears shifted ahead of the NIR light curves at a time of $\sim 15 \text{ days}$. The similar shapes of these light curves indicate that the origins of the X-ray emission and NIR emission are related to each other. On the other hand, the time gap between these two emissions denotes that the X-ray source and NIR source are separated from each other as much as the time gap. Bloom et al. (2011) suggested that the X-ray source is in the close vicinity of the black hole due to the fact that the X-ray emission shows very rapid, high variability, while the IR and radio sources are located a large distance from the black hole on account of the relatively smooth and small variability. They argued that the jet generated by the black hole collides with the surrounding medium where the electrons are accelerated by the jet. These high-speed electrons emit IR to radio photons through synchrotron radiation.

The jet seems to be nearly turned off at $\Delta t \approx 500 \text{ days}$ in light of the fact that there is an abrupt decrease in flux of a factor of $\sim 10$ or more, which can be seen in all the Swift/XRT, Chandra, and XMM-Newton data (Levan & Tanvir 2012;
Zauderer et al. (2013). This late-stage turn-off of the X-ray flux is also shown in Figure 5. If the jet was turned off, then the transient components of the NIR fluxes must be quenched following the X-ray flux, and it is expected that the fluxes of the pure host galaxy of Swift J1644+57 were revealed at that time. As we can see in Figure 6, which shows the $H$-, $K$- and $J$-band light curves in linear scale, the fluxes of the $H$ and $K$ bands converge to single values at later-time. Furthermore, the latest $H$-band magnitude is nearly the same as that of the host galaxy of the F160W-band images, shown in the results of the model fitting in Section 3. This evidence indicates that it is reasonable to regard the NIR $(Y, J, H, \text{ and } K\text{ band})$ fluxes of the last data, taken at $\Delta t = \sim 700$ or 884 days, as those of the pure host galaxy.

The left panel of Figure 7 shows the light curves of the CQUEAN $i$- and $z$-band and the UKIRT $Z$-band data. In the case of the $Z$ band, the fluxes from the object slightly decrease with time. We also regard the flux of the last data, that is the UKIRT $Z$-band data, as the $Z$-band flux of the host galaxy since it is observed far beyond the expected quenching time of jet. On the other hand, the $i$-band fluxes are virtually constant, demonstrating that the transient components are basically non-existent in the $i$ or bluer bands (Figure 3; Burrows et al. 2011; Levan et al. 2011). We take the flux of the last data of the $i$ band as that of the host galaxy. The number of CQUEAN $g$- and $r$-band data points are scarce compared to the NIR data and the last data were observed at early times ($\Delta t = 25.7, 217.5$ days, respectively). However, there is little or no change between the very early-time magnitudes from Levan et al. (2011) and our $g$- and $r$-band magnitudes in the same way as the fluxes of the $i$ and $F606W$ bands. Therefore, we consider the $g$- and $r$-band fluxes of the last epoch data as those from the host galaxy. Furthermore, we also consider the magnitude of the single Sérsic model of the stacked $HST$ WFC3 $F606W$ image as that of the host galaxy since the point source contribution to the whole flux is negligible.

The right panel of Figure 7 shows the light curves of the Spitzer IRAC 3.6 and 4.5 $\mu m$ bands. The magnitude changes in these bands are more significant than those for the other optical/ NIR bands. The fluxes from the transient component seem to be non-negligible even in the last epoch data ($\Delta t = 333$ days) because the last IRAC epochs were still in the rapidly decreasing phase. Therefore, we consider the fluxes of the last epoch IRAC data to be the upper limit fluxes of the host galaxy.

The multi-band magnitudes of the host galaxy of Swift J1644+57 are shown in Table 4. We took the Galactic extinction of photometric data into account based on Schlafly & Finkbeiner (2011). We added the $B$-band photometric data from Levan et al. (2011) to expand the data points to the short wavelength band.

The temporal change of the observed SED of Swift J1644+57 are summarized in Figure 8. The fluxes in redder bands show substantial changes with time. Meanwhile, bluer band fluxes are constant. This red feature of the transient has been suggested to be due to dust extinction. From previous studies, it is known that the hydrogen column density of the X-ray source is large ($N_{H} \sim 10^{22} \text{ cm}^{-2}$), meaning the line of sight to the SMBH has a very large extinction value ($A_V = 4.5-10$; Bloom et al. 2011; Burrows et al. 2011; Levan et al. 2011; Shao et al. 2011; Saxton et al. 2012).

5. SED FITTING

We performed SED model fitting of the multi-band fluxes of host galaxy of Swift J1644+57 in order to determine the properties of the host galaxy, such as the stellar mass ($M_*$) which is an important parameter for the $M_{BH}$ estimation. We utilized the code Fitting and Assessment of Synthetic Templates (FAST;13 Kriek et al. 2009), which is a public SED fitting tool for the investigation of galaxy properties using photometric data ranging from the UV to IR. The code is based on the IDL and fits of UV to IR stellar population templates to photometric data or galaxy spectra. FAST runs with the method of $\chi^2$ fitting and using stellar population grids to derive the best-fit model and its parameters.

13 http://astro.berkeley.edu/~mariska/FAST.html
We used the 2003 version of the Bruzual & Charlot (BC03) model (Bruzual & Charlot 2003) for the stellar population model. There are three initial mass functions (IMFs) available in FAST (Salpeter 1955; Kroupa 2001; Chabrier 2003). We chose the Salpeter IMF. To define the star formation history (SFH), we assumed an exponentially decreasing star formation rate (SFR).

The stellar population was modeled with the e-folding time scales $6.5 \log \tau/\text{yr} \leq 11.0$ with a step size of 0.1 and ages of $8.0 \leq \log \tau/\text{yr} \leq 10.3$ with a step size of 0.1. We used several metallicity values such as $Z = 0.004, 0.008, 0.02, \text{and} 0.05$. The model SEDs were attenuated by dust, for which we used attenuation curves based on Calzetti et al. (2000). We adopted $0.0 \leq A_V \leq 3.0$ with a step size of 0.1. All the input parameters for the SED fitting are summarized in Table 5.

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Figure 9 shows the SED fitting result. The two Spitzer data were treated as the upper limit fluxes of the host galaxy. The estimated stellar mass of the host galaxy is 
\[ M_{\star} \log(\text{mass}) = 9.14 \pm 0.10 \text{ with a step size of 0.1} \]
and the specific SFR is 
\[ \log(\text{sSFR yr}^{-1}) = -10.621 \pm 0.90 \text{ with a step size of 0.1} \]. Levan et al. (2011) derived an SFR of 0.3–0.7 \( M_\odot \text{yr}^{-1} \) from the H\( \alpha \) and [O II] emission line luminosities. The value of 0.3 \( M_\odot \text{yr}^{-1} \) from H\( \alpha \) is consistent with our 1σ upper limit. The SFR from the [O II] line (0.7 \( M_\odot \text{yr}^{-1} \)) is about twice as large, but the [O II] line-based SFRs are known to be dependent on physical condition such as the reddening and metallicity (e.g., Kewley et al. 2004), and less reliable than H\( \alpha \)-based SFRs. Another possible cause of the discrepancy is the different timescales probed by different SFR indicators (emission line indicators probing recent star formation). Levan et al. (2011) estimated

Figure 7. Light curves of the CQUEAN i and z bands, the UKIRT Z-band data, and Spitzer IRAC 3.6 and 4.5 \( \mu m \) bands. Note that the z-band flux decreases with time, while the i-band flux is almost constant with time. Considerable magnitude changes in the Spitzer IRAC 3.6 and 4.5 \( \mu m \) bands can be seen in the right plot.

Table 4

| Band | Magnitude (AB) |
|------|----------------|
| B    | 24.24 ± 0.10 (Levan et al. 2011) |
| g    | 23.67 ± 0.19  |
| r    | 22.72 ± 0.01  |
| i    | 22.73 ± 0.06  |
| Z    | 22.25 ± 0.04  |
| Y    | 22.16 ± 0.06  |
| J    | 22.18 ± 0.07  |
| H    | 21.96 ± 0.08  |
| K    | 21.55 ± 0.10  |
| 3.6 \( \mu m \) | 21.70 ± 0.07 (Including transient) |
| 4.5 \( \mu m \) | 21.57 ± 0.08 (Including transient) |

Note. Magnitudes are corrected by Galactic extinction based on Schlafly & Finkbeiner (2011).

Figure 8. Temporal change of the SED of Swift J1644+57. The fluxes in the redder bands show the substantial changes with time, whereas the bluer-band fluxes do not vary with time.

Table 5

| Parameter | Value |
|-----------|-------|
| \( \tau \) (e-folding timescale of stellar population) | 6.5 \( \leq \log(\tau/\text{yr}) \leq 11.0 \) with a step size of 0.1 |
| \( t \) (age of stellar population) | 8.0 \( \leq \log(\text{yr}) \leq 10.3 \) with a step size of 0.1 |
| IMF (initial mass function) | Salpeter (1955) |
| Z (metallicity) | 0.004, 0.008, 0.020, 0.050 |
| Extinction law | Calzetti et al. (2000) |
| \( A_V \) (V-band attenuation for stellar population in magnitude) | 0.0 \( \leq A_V \leq 3.0 \) with a step size of 0.1 |
the multi-band fluxes of the host galaxy in Table 4. Two Spitzer data are the upper limit fluxes. The $\chi^2$ value for the fit is 1.64.

$E(B - V)_{\text{gas}} = -0.01 \pm 0.15$ mag, i.e., no extinction using the intensity ratio of the H$\alpha$ and H$\beta$ lines. This is consistent with our SED fitting result $A_V = 0.00^{+0.07}_{-0.00}$. The $\chi^2$ value for the fit is 1.64.

The host galaxy of Swift J1644+57 is a low-mass, low SFR galaxy with low extinction. Also, it seems to have experienced a rapid decline of SFR not very long ago. This fits in well with a recent suggestion by Arcavi et al. (2014) that the host galaxies of tidal disruption events are E+A galaxies with $<1$ Gyr stellar population and low or no SFRs.

The output parameters are given in Table 6. The errors correspond to 1σ confidence intervals derived from 100 times Monte Carlo simulations in which the input photometric data are changed according to their errors.

We also tried the Chabrier IMF instead of the Salpeter IMF for the fit. The change of the IMF influenced to the stellar mass, decreasing it by $\sim 0.25$ dex.

We also fit the SED model with the Maraston (2005) stellar population instead of the BC03 model. We set the input parameter ranges to be identical to the case of the BC03 stellar populations. The results were nearly identical to the BC03 result.

Our analysis of the host galaxy shows that the host galaxy is bulge-dominated and nearly extinction free ($A_V \sim 0$ mag). On the other hand, the spectral properties of the nuclear transient suggest high extinction ($A_V \sim 6$ mag). These two facts may appear contradictory, but we note that a significant amount of dust can be found easily in nuclear region of bulge-dominated galaxies when their nuclei are active. For example, the hosts of luminous active galactic nuclei (AGNs) are mostly early-type, bulge-dominated galaxies (e.g., Hong et al., 2015), and such AGNs are known to contain a significant amount of dust in their nuclear region in the form of a hot or warm dusty torus (e.g., Kim et al., 2015).

### 6. DISCUSSION ON BLACK HOLE MASS

Our results on the properties of the host galaxy of Swift J1644+57 can be summarized as follows. It is a bulge-dominated galaxy ($B/T = 0.83 \pm 0.03$). The mass of the host galaxy is somewhat low at $10^{9.14} M_\odot$, even though the galaxy is bulge-dominated. Now we estimate the mass of the SMBH that played the main role in the transient phenomenon.

It is now generally accepted that SMBHs ($10^6 - 10^{10} M_\odot$) reside in the bulges of all massive galaxies. Tight scaling relations have been derived between SMBH mass and several physical properties of the bulges (velocity dispersion, mass, luminosity, etc.) in many previous studies (Magorrian et al., 1998; Ferrarese & Merritt, 2000; Gebhardt et al., 2000; McLure & Dunlop, 2002; Marconi & Hunt, 2003; Häring & Rix, 2004; Aller & Richstone, 2007; Hopkins et al., 2007; Gültekin et al., 2009; Kormendy & Bender, 2009; Sani et al., 2011; Kormendy & Ho, 2013). Some argue that ellipticals and classical bulges follow identical relations, while the pseudobulges follow a somewhat different relation with large scatter (Hu, 2008; Kormendy et al., 2011; Sani et al., 2011; Kormendy & Ho, 2013). We conclude from the best-fit galaxy models that the host galaxy of Swift J1644+57 has a classical bulge, and we have also found the minor possibility of a pseudobulge with $B/T = 0.36$. For now, we consider only the best model, that is, the case of the host galaxy having a classical bulge and being bulge-dominant.

In order to estimate the central SMBH mass in the host galaxy of Swift J1644+57, we used the scaling relation between $M_{\text{BH}}$ and the stellar mass of the bulge ($M_{*,\text{bul}}$). We expect that a large part of the stellar mass derived in Section 5 belongs to the bulge component. Sani et al. (2011) present the $M_{\text{BH}} - M_{*,\text{bul}}$ relation, where $M_{*,\text{bul}}$ is directly obtained from the bulge luminosity ($L_{\text{bul}}$) of Spitzer 3.6 $\mu$m and the calibrated $M_{*,\text{bul}} - L_{\text{bul}}$ relation. They excluded pseudobulges when constructing the relation. The relation is

$$\log(M_{\text{BH}}/M_\odot) = \alpha + \beta \times \left[ \log(M_{*,\text{bul}}/M_\odot) - 11 \right], \quad (1)$$

where $\alpha = 8.16 \pm 0.06$, $\beta = 0.79 \pm 0.08$, and the intrinsic scatter is 0.38 ± 0.05. The estimated mass of the SMBH is $10^{6.7 \pm 0.4} M_\odot$ based on the stellar mass of the host galaxy and the above relation. If we consider the $B/T$ then $= 0.83$ and assume that the mass-to-light ratio is constant in the bulge and disk, the stellar mass is decreased by ~0.1 dex. It leads to a decrease in $M_{\text{BH}}$ by ~0.1 dex.

The tight scaling relations between $M_{\text{BH}}$ and the host galaxy properties suggest a close link between the SMBH growth and the galaxy evolution. There may be a cosmic evolution of the scaling relations, for which there have been various studies.
The tidal disruption of normal stars by a black hole is not possible for \( M_{\bullet}/L_{\ast} \sim 10^{4} M_{\odot} \), as implied from the pseudobulge fit of our data, currently one can barely do so by relying on results from low-mass AGNs (Barth et al. 2005; Greene et al. 2008; Jiang et al. 2011; Xiao et al. 2011). In such a case, an \( M_{\bullet} \) value between \( 10^{2} \) and \( 10^{6.3} M_{\odot} \) is possible (Figure 32 of Kormendy & Ho 2013). Overall, if the host galaxy harbors a pseudobulge, then we can only loosely constrain \( M_{\bullet} \) to have a value between \( 10^{5} \) and \( 10^{7} M_{\odot} \), considering our current poor knowledge of the \( M_{\bullet} \) value in pseudobulges.

It is also known that a small fraction of pseudobulges have a Sérsic index of \( n > 3 \). The best example is Pox 52, for which \( n \sim 3.6\sim 4.3 \), \( M_{\bullet} \sim 2 \times 10^{5} M_{\odot} \), and \( M_{\bullet} \sim 10^{9} M_{\odot} \) (Barth et al. 2004; Thornton et al. 2008). Therefore, even if we accept the Sérsic index of \( n = 3.43 \) as the best-fit result, we need to keep this kind of caveat in mind.

Figure 10 shows our overall results on \( M_{\bullet} \) and the results from the previous studies we mentioned in Section 1. It shows that our favorite results are compatible with the previous rough estimates from Burrows et al. (2011) and Levan et al. (2011), who also used scaling relations. However, our results are improved compared to the previous results, by revealing that the host galaxy has a significant bulge component through a two-dimensional bulge + disk decomposition of the surface brightness profile, and removing the transient component in NIR light using a long-term light curve. The \( M_{\bullet} \) limit could be much looser (the dashed line) if the host galaxy harbors a pseudobulge. A critical test of the pseudobulge model would be to obtain a deep, high-resolution image to see how the surface...
brightness profile behaves at the outer region of the host galaxy.

7. SUMMARY

We investigated the host galaxy properties of the tidal disruption event Swift J1644+57 through morphology analysis, light curve analysis, and SED fitting. We also estimated the $M_{\text{BH}}$ which played the main role in this phenomenon through scaling relations.

We decomposed the surface brightness profile of the host galaxy based on high-resolution HST WFC3 images. We found that the host galaxy of Swift J1644+57 is a bulge-dominated galaxy which is well described by a single Sérsic model with a Sérsic index of $n = 3.43 \pm 0.05$. If we add a disk component, then the bulge to total host galaxy flux ratio $(B/T)$ is $0.83 \pm 0.03$, still indicating a bulge-dominant galaxy. We conclude that the host galaxy of Swift J1644+57 has a classical bulge and the stellar mass, this galaxy resembles M32, a small companion galaxy of M31.

We estimated the central $M_{\text{BH}}$ through scaling relations. The mass of the SMBH is estimated to be $10^{6.7 \pm 0.4} M_\odot$ from $M_{\text{BH}} - M_{\ast,\text{bul}}$ and $M_{\text{BH}} - L_{\text{bul}}$ relations for the $K$ band. However, the limit on $M_{\text{BH}}$ can be much looser if the host galaxy has a pseudobulge. Future high-resolution, deep imaging should be able to unambiguously distinguish the two possibilities.

This work was supported by the National Research Foundation of Korea (NRF) grant No. 2008-0060544, funded by the Korea government (MSIP). We thank the observers who obtained the CQUEAN and UKIRT data that were used in our analysis. This paper includes the data taken at the McDonald Observatory of the University of Texas at Austin. At the time of the UKIRT observation, UKIRT was operated by the Joint Astronomy Centre on behalf of the Science and Technology Facilities Council of the U.K. This work is based in part on observations made with the Spitzer Space Telescope, which is operated by the Jet Propulsion Laboratory, California Institute of Technology on behalf of NASA. We acknowledge the use of public data from the Swift data archive. C.P., T.S., and N.G. acknowledge support from the NASA research grant NNX10AF39G. M.I. gratefully acknowledges the hospitality and support of the Korea Institute of Advanced Study where part of this work was carried out.