KUG 0200-096: Dwarf Antennae Hosting a Tidal Dwarf Galaxy

Sanjaya Paudel1, Chandreyee Sengupta2, and Suk-Jin Yoon1,2

1 Center for Galaxy Evolution Research, Yonsei University, Seoul 03722, Republic of Korea; sanipaudel@gmail.com, syoon0691@yonsei.ac.kr
2 Department of Astronomy, Yonsei University, 50 Yonsei-ro, Seodaemun-gu, Seoul, Republic of Korea; sengupta.chandreyee@gmail.com

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Abstract

We study a gas-rich merging dwarf system KUG 0200-096. Deep optical imaging reveals an optically faint tail with a length of 20 kpc, giving a visual impression of tidal antenna similar to NGC 4038/39. The interacting dwarf galaxies have B-band absolute magnitudes of −18.06 and −16.63 mag. We identify a young stellar clump with a stellar mass of $2 \times 10^7 M_\odot$ at the tip of the antenna, possibly a tidal dwarf galaxy (TDG). The putative TDG candidate is quite blue with a $g-r$ color index of −0.07 mag, whereas the interacting dwarf galaxies have $g-r$ color indices 0.29 and 0.19 mag. The TDG is currently forming stars at the rate of 0.02 $M_\odot$ yr$^{-1}$. We obtained H1 21 cm line data of KUG 0200-096 using the Giant Metrewave Radio Telescope to get a more detailed view of neutral hydrogen (H1) emission in interacting dwarf galaxies and its TDG. Evidence of a merger between the dwarf galaxy pair is also present in H1 kinematics and morphology where we find the H1 contents of the interacting pair is disturbed, forming an extended tail toward the TDG. The H1 velocity field shows a strong gradient along the H1 tidal tail extension. We present a comparative study between the Antennae galaxy, NGC 4038/39, and KUG 0200-096 in both optical and H1 gas properties and discuss the possible origin of the KUG 0200-096 TDG.

Key words: galaxies: dwarf – galaxies: evolution – galaxies: formation – galaxies: interactions – galaxies: ISM

1. Introduction

The Antennae (NGC 4038/39) is a textbook example of a pair of merging disk galaxies (Arp 1966; Struck 1999). As such, they have been studied in detailed observation (Amram et al. 1992; Kunze et al. 1996; Neff & Ulvestad 2000; Gao et al. 2001; Gordon et al. 2001; Hibbard et al. 2001; Whitmore et al. 2005, 2014; Zhang et al. 2010) and reproduced in various numerical simulations (Toomre & Toomre 1972; Barnes 1988; Karl et al. 2010; Teyssier et al. 2010; Renaud et al. 2015; Lahén et al. 2018). The system displays a prominent pair of tidal tails that extend a projected distance of 20', and the two merging disks are visibly distinct (Schweizer 1978). The latter has been assumed to be an indication of an early merger state, putting the system in the first place of the Toomre (1977) merger sequence. One important aspect of the Antennae system has been the discovery of the ongoing formation of tidal dwarf galaxies (TDGs) at the tip of the antenna (Mirabel et al. 1992; Hibbard et al. 2001).

TDGs are the most massive substructures born in gas-rich mergers. Their total mass is similar to that of dwarf galaxies ($M_* < 10^7$). Made out of tidal material (gas and stars) ejected from galaxies into the intergalactic medium, they are independent gravitationally bound systems, usually supported by rotation. Their dynamical status qualifies them as “galaxies” (see Duc 2012, for a review on TDGs), although they are nascent galaxies, they are not necessarily always in dynamical equilibrium (Lelli et al. 2015). The importance of TDGs among the dwarf population is rather controversial. The idealized numerical simulations of galaxy–galaxy collisions made by Bournaud & Duc (2006) suggest that only a fraction of massive TDGs might survive long enough to evolve as independent galaxies. Objects that are not kicked out from their parent’s potential well are subjected to dynamical friction, and gradual reduction of orbital energy plunges them into the host system where they could suffer destructive tidal forces from their host galaxies (Mayer et al. 2001; Fleck & Kuhn 2003), or could be destabilized by the effects of ram pressure (Smith et al. 2013).

While massive galaxy interactions have been studied in great detail in the past, very little is known about the evolution of dwarf–dwarf interactions and mergers. There has been growing interest in the dwarf–dwarf interaction in recent literature, and in the last few years, a number of studies have presented observational evidences of the merging dwarf galaxies (Martínez-Delgado et al. 2012; Paudel et al. 2015; Stierwalt et al. 2015; Pearson et al. 2016). In addition, many star-bursting dwarf galaxies show disturbed H1 kinematics as a signature of tidal interactions (Lelli et al. 2014). Studying formation TDGs in the dwarf–dwarf merging systems is important, as the TDGs born out of colliding dwarf galaxies are expected to have different environments. Owing to the shallow potential well of host galaxies, the newborn TDGs are subjected to a significantly low level of harsh tidal force from the parent. Low-mass galaxies also have lower levels of X-ray emission therefore a weaker ram pressure stripping effect. This provides a higher survival probability of TDGs born outside of dwarf galaxy collisions.

In this paper, we present a unique example of a low-mass ($M_* \approx 4 \times 10^7$) Antennae system, KUG 0200-096, where we identify a TDG at the tip of the tidal tail.

Throughout the paper, we adopt a luminosity distance of 68 Mpc ($m-M=34.1$) and a scale of 0.32 kpc arcsec$^{-1}$ valid for $H_0=71$ km s$^{-1}$ Mpc$^{-1}$.

2. KUG 0200-096: The Dwarf Antennae

At a sky position R.A. = 02:02:38.77 decl. = –09:22:13.2 and redshift $z = 0.018$, we find an interacting pair of star-forming dwarf galaxies, KUG 0200-096, with an extended tail of stellar stream. According to NED query, KUG 0200-096 is located in an isolated environment. It’s immediate neighbor galaxy is NGC 0787 at a sky-projected distance of 693 kpc, and the two have a relative line-of-sight radial velocity 692 km s$^{-1}$.
As far as our NED query results, we find no other companion, not even dwarf galaxies around KUG 0200-096 within the area of 700 kpc and $\pm 1000$ km s$^{-1}$ velocity range.

Figure 1 reveals the remarkable tidal nature at the periphery of KUG 0200-096. The color image is obtained from the SDSS sky-server, which is prepared by combining $g$, $r$, and $i$-band images (Lupton et al. 2004). In the right panel, we show a much deeper gray-scale $g$-band image, which we have obtained from the Canada–France–Hawaii Telescope (CHFT$^3$) archive. Both have a $3'\times3'$ field of view. We label the interacting pair of dwarf galaxies D1 and D2. The sky-projected separation between the two galaxies (D1 and D2) is 9 kpc. It is apparent that D2 is more disturbed than D1, forming an antenna-like prominent tidal tail that mimics one antenna of NGC 4038/39 (The Antennae galaxy). The shape of the antenna is nearly a semi-circle, and the surface brightness is not uniform; it decreases toward the end. In fact, this is almost invisible in the color SDSS image, and we can only spot a blue clump, quite separated from the interacting dwarf pair main body.

We consider the blue clump at the tip of the antenna, highlighted by a green circle, as a potential TDG candidate. The left color image reveals that the TDG is much bluer compared to the D1 and D2 which, indeed, will be verified by measured $g - r$ color (see below). TDG position in the sky is R.A. = 02:02:39.14 and decl. = −09:23:23.4. It is well separated from the interacting galaxies’ main bodies with distances from D1 and D2 of 22 and 14 kpc, respectively.

### 3. Data Analysis

#### 3.1. Analysis of Optical Data

To perform a photometric analysis and measure the total luminosity, we retrieved archival images from the SDSS-III database (Abazajian et al. 2009). Since the SDSS-III data archive provides well calibrated and sky-background subtracted image, no further effort has been made in this regard. However, we used a simple and similar approach to subtract the sky-background count as in Paudel & Ree (2014). We performed the aperture photometry with different aperture sizes to measure the total flux of objects of interest, i.e., D1, D2 and the potential TDG candidate. The sizes of apertures were selected visually where we used a wide enough aperture to secure all flux in the region of interest. Before performing the aperture photometry, we masked all unrelated foreground and background objects manually.

We list the positions, absolute magnitudes, and stellar masses of the interacting dwarf member and the putative TDG in Table 1. The derived magnitudes were corrected for Galactic extinction using Schlafly & Finkbeiner (2011), but not for the internal extinction. We convert the SDSS $g$-band magnitudes to $B$-band magnitudes using equation provided on the SDSS website.$^4$

To estimate the stellar masses, we use a calibration provided by Bell et al. (2003) appropriate for the observed $g - r$ color. Bell et al. (2003) assume a simple stellar population with a single burst of star formation to derive a relation between the mass-to-light ratio and galaxy color where a typical scatter is 0.2 dex. Indeed, galaxy star formation histories are complex. However, it is shown that scatter in the mass-to-light ratio derived from different star formation histories for a given color is also scattered within $\pm 0.2$ dex, see Section 4.3 in Zhang et al. (2017). Therefore, we consider 0.2 dex as a typical conservative error on our stellar mass estimates.

The interacting dwarfs, D1 and D2, have $B$-band absolute magnitudes of $−18.06$ and $−16.63$ mag, respectively. We find that both interacting member dwarf galaxies have approximately similar $g - r$ color indices, i.e., 0.29 and 0.19 for D1 and D2, respectively. But the TDG is significantly blue, with a

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$^3$ http://www.cfht.hawaii.edu

$^4$ http://www.sdss3.org/dr8/quantities/sdssUBVRITransform.php
The typical error on the SDSS magnitudes is 0.01 mag. The stellar mass, given in column 8, is derived from the mass-to-light ratio obtained from Bell et al. (2003) for the color $g - r$, where we expect a conservative error on our estimate is 0.2 dex. We list star formation rate in column 9, which is estimated from the FUV magnitudes. In column 10, we give H I mass, were the D1 value represents H I mass of entire the system. Radial velocity measured from H I kinematics is listed in the last column.

As their blue color indicates ongoing star-forming activity, we use GALEX UV images to calculate ongoing star formation rates. We retrieved The GALEX all-sky survey (Martin et al. 2005) archival images, see Figure 2. Interestingly, the stellar stream/antenna is also visible in GALEX UV images and the TDG is quite prominent in both the FUV and NUV bands. We perform aperture photometry as done in the SDSS images in both FUV and NUV-bands. We derive the star formation rate from the FUV flux using a calibration provided by Kennicutt (1998). The values are listed in Table 1. UV-optical colors (FUV–g) of D1 and D2 are 2.3 and 1.9 mag, respectively, and that of the TDG is significantly blue, i.e., 0.26 mag.

Finally, we performed aperture photometry on the entire system. For this, we first manually masked all non-related objects and selected a large aperture that includes the entire system. The total B-band luminosity is $M_B = -18.69$, and the $g - r$ color index is 0.29 mag. We derived a total stellar mass $M_*$, total = $3.9 \times 10^9 M_\odot$, and a total star formation rate $SFR_{total} = 0.46 M_\odot$ yr$^{-1}$. From these estimates, we calculate that the TDG mass fraction is only $\leq 0.5\%$ of the entire system. A significant increase in the stellar mass of the entire system in comparison with sum of the stellar masses of three components, D1, D2 and TDG, could be because of following three reasons: (1) we may have missed some light from extended parts, particularly the stellar stream, which is only accounted for during overall photometry using a single large aperture; (2) there might be contamination from the foreground and background structure, which we have misidentified; and (3) different star formation histories, which produce slightly different mass-to-light ratios. However, we expect that all three might have contributed to some extent to increase the stellar mass of the overall system.

The SDSS fiber spectroscopy has targeted the brighter galaxy, D1, and gives its redshift $z = 0.01801$. We obtain the optical spectrum of D1 from the the SDSS archives, which are observed with a 3″ diameter fiber. They exhibit the emission lines typical of H II regions as well as relatively strong absorption for the early Balmer lines H$\delta$, γ, and β. The Hα equivalent width measured in the SDSS fiber spectrum is 22 Å. This value is not high enough to consider the galaxy a star-burst; instead, this value is typical for local Blue Compact Dwarf galaxies (BCDs; Meyer et al. 2014). Emission line metallicity derived from ration of H$\alpha$/[N II] is 8.3 and star formation rate derived from H$\alpha$ emission line flux is 0.015 $M_\odot$ yr$^{-1}$, which is significantly lower than the SFR derived from the FUV flux. However, note that 3″ diameter fiber spectroscopy only represents the central part of the galaxy, and the SFR derived from the FUV flux is summed over the entire galaxy.

### 3.2. Radio 21 cm Observation
To study the H I content of the system in detail, we carried out H I interferometric observations of KUG 0200–096, using the Giant Metrewave Radio Telescope (GMRT) located at Pune, India. The system was observed on 2017 June 15 as part of our observing proposal “Formation of TDG during dwarf–dwarf merger.” Part of the data from this project has already been published in Paudel & Sengupta (2017) where we describe the observation setup. In brief, a baseband bandwidth of 16 MHz was used for the observations, yielding a velocity resolution $\sim 7$ km s$^{-1}$. The GMRT primary beam at the L band is 24′, and the synthesized beams of the images presented in the paper are $43''4 \times 34''6$ (low resolution) and $24''8 \times 19''5$ (high resolution). At the adopted distance of KUG 0200–096, 68 Mpc, the beams of 43″ and 25″ correspond to the physical resolutions of 14 kpc and 8 kpc, respectively. The data was analyzed using the software AIPS6, and the procedure followed was similar to that explained in Sengupta et al. (2017).

Figure 3 (top panel) shows the contours from the low-resolution integrated H I map overlaid on the CHFT $r$-band image. The H I emission is mainly concentrated around D1 and D2 with an extension of tenuous emission in the direction of antenna. An H I tail extends toward the antenna approximately aligned to the stellar stream. Except the H I tail, we do not

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**Table 1** Photometric Properties

| Galaxy | R.A. (h:m:s) | Decl. (d:m:s) | $m_r$ | $g - r$ | $m_{FUV}$ | $M_B$ | $M_*$ | SFR | $M_{HI}$ | $z$ | $V_r$ (km s$^{-1}$) |
|--------|-------------|--------------|-------|--------|----------|-------|-------|------|---------|----|------------------|
| D1     | 02:02:38.77 | −09:22:13.2  | 15.76 | 0.29   | 18.06    | −18.06| 9.27  | −0.68| 9.3     | 0.018 | 5376             |
| D2     | 02:02:39.95 | −09:22:43.0  | 17.32 | 0.19   | 19.28    | −16.63| 8.74  | −1.17| 10      | ...  | 5355             |
| TDG    | 02:02:39.14 | −09:23:23.4  | 20.36 | −0.07  | 20.62    | −13.93| 7.27  | −1.70| 8.1     | ...  | 5441             |

Note. The magnitudes are corrected for galactic extinction, and the $B$-band magnitude is obtained from the SDSS $g$-band magnitude using the conversion formula provided by the SDSS. The typical error on the SDSS magnitudes is 0.01 mag. The stellar mass, given in column 8, is derived from the $r$-band luminosity and the mass-to-light ratio obtained from Bell et al. (2003) for the color $g - r$, where we expect a conservative error on our estimate is 0.2 dex. We list star formation rate in column 9, which is estimated from the FUV magnitudes. In column 10, we give H I mass, were the D1 value represents H I mass of entire the system. Radial velocity measured from H I kinematics is listed in the last column.

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5. [http://www.ncra.tifr.res.in/ncra/gmrt](http://www.ncra.tifr.res.in/ncra/gmrt)
6. [http://www.aips.nrao.edu](http://www.aips.nrao.edu)
detect any extended or diffuse H I features around the system. The H I column density at the tail region is very low, ∼2–4 × 10^{19} cm\(^{-2}\).

The H I map reveals two peaks in H I column density, suggesting that both interacting galaxies may be gas rich. The misalignment of the optical and H I tidal remnants is more pronounced in the high-resolution map compared to the low-resolution map (see lower panel Figure 3). The H I is seen to overlap with the TDG forming a bridge to the main system with no optical counterpart. On the TDG, the peak H I column density is 4 × 10^{19} cm\(^{-2}\). The TDG is quite compact in the optical, but our resolution limit of H I observation does not allow us to conclude whether the gas structure in TDG is already detached or still part of the tidal tail.

Figure 3 (bottom panel) shows the H I velocity field of the KUG 0200-096 system in high resolution. While signs of an interacting system are clear, velocity fields of the individual galaxies (D1 and D2) cannot be resolved due to the lack of spatial resolution. However, we can infer that D2 has lower line-of-sight velocity than D1. Figure 4 shows the integrated spectrum of the combined system where we mark the optical velocity of D1 by the solid line and the H I velocity of the TDG by the dashed line. The TDG H I velocity represents the peak H I velocity in the H I spectrum of region around TDG. Interestingly, the gas around the TDG has velocities closer to D1.

The H I tidal tail structure and kinematics are further illustrated in the channel maps, shown in Figure 5. The northern, eastern, and the southern crosses represent D1, D2, and the TDG, respectively. H I emission is detected in the system in the velocity range of 5296 to 5488 km s\(^{-1}\). The origin of the H I connection of the TDG to the parent interacting pair becomes clearer in the channel maps. While the optical image shows the stellar tidal tail to originate in D2, the H I channel maps indicate the H I tidal tail connecting the TDG to KUG 0200-096 originates at D1, between velocities 5402 and 5488 km s\(^{-1}\). The integrated H I flux density of the system is 1.4 Jy km s\(^{-1}\) and in the TDG region is 0.4 Jy km s\(^{-1}\), which corresponds to H I mass of 1.5 × 10^9 and 4 × 10^8 M_\odot, respectively. The H I gas-to-light ratio, log(M_{HI}/L_B) for the TDG and overall system is 0.4 and −0.3, respectively.

4. Discussion

We have presented the case of a merging dwarf galaxies pair in an isolated environment where we found a TDG is forming...
at the tip of tidal stream similar to the well-known interacting system NGC 4038/39 (The Antennae galaxy). The TDG has a stellar mass $M_* = 1.9 \times 10^7 M_\odot$, which is 0.5% of the entire merging system. It is located at 22 kpc sky-projected distance from the main merging galaxy. It is blue with a $g - r$ color index of $-0.07$ mag and is gas rich with an H$\alpha$ gas-to-light ratio of $\log(M_{H\alpha}/L_\odot) = 0.4$.

4.1. Tidal Interaction and Star formation

KUG 0200-096, no doubt, provides a great example of gas-rich merging dwarf galaxies. The interacting galaxies, D1 and D2, have $B$-band absolute magnitudes $-18.06$ and $-16.63$ mag, which are similar to those of the LMC/SMC pair, well-known interacting dwarf galaxies in our vicinity. Several
physical properties of KUG 0200-096, i.e., color, metal content, and SFR, are fairly similar to the typical BCDs, and there is little doubt that its star formation activity is affected, if not triggered, by the interaction.

LMC/SMC do not host star-forming regions outside of the galactic main body, although they show substantial extension of gas structure (D’Onghia & Fox 2016). However, in our previous publication (Paudel et al. 2017), we have identified a TDG located in a stellar bridge between two interacting dwarf galaxies, which have similar star formation and physical properties to LMC/SMC.

We find that on average, KUG 0200-096 has typical star-forming properties of BCDs. In Figure 6, we show a relation between star formation rate and $B$-band magnitude for star-forming galaxies. The comparison sample is taken from Lee et al. (2009), who study star-forming activity of local volume (<11 Mpc) star-forming galaxies where star formation rates are also derived from FUV flux. We find no enhanced star formation for overall $B$-band magnitude of the system compared to a sample of star-forming galaxies from the local volume. However, the TDG is located at the upper edge of scattered data.

The gas mass fraction of the TDG is high compared to the overall gas mass fraction of the system, but due to the large beam size of the GMRT observation, we cannot rule out the possibility of some contamination from the host galaxies. In any case, the value of gas-to-stellar mass ratio of the TDG, log($M_{\text{HI}}/M_{\text{st}}$) = 0.83, is perfectly scaled with the relation of log($M_{\text{HI}}/M_{\text{st}}$) and stellar mass, see Popping et al. (2015) Figure 3.

The elongated tails are a clear sign of tidal interaction of nearly equal-mass gas-rich disk galaxies. According to the Toomre sequence (Toomre & Toomre 1972), KUG 0200-096 is probably in an early-stage of interaction. In comparison to the Antennae system, both interacting galaxies are clearly separated, which may hint that the interaction in KUG 0200-096 is young compared to the interaction between NGC 4038 and NGC 4039.

Numerical simulations of this interacting system could help to assess the timescale of interaction and further morphological evolution of the TDG and merging remnant, but they are beyond the scope of this paper.

4.2. Formation of TDGs during Dwarf–Dwarf Merger

The merging probability of low-mass galaxies decreases in a low-redshift universe, and, as a result, the chance of formation of TDGs by merger of dwarf galaxies is also low (De Lucia et al. 2006). This makes low-redshift dwarf–dwarf mergers an interesting phenomena to study. It has been found that dwarf–dwarf interactions are more likely to happen in isolated environments than in the groups or clusters (Stierwalt et al. 2015; Paudel et al. 2018). Given that dwarf galaxies located in isolated environments are gas rich, mostly the Blue Compact Dwarf galaxy (BCD) type, it is not surprising that TDGs may form frequently in these gas-rich dwarf–dwarf mergers. In fact, we also identified a newborn TDG in our previous study of merging dwarf galaxies, although they are in a group environment (Paudel et al. 2015; Paudel & Sengupta 2017).

KUG 0200-096 is noteworthy for the presence of a stellar stream hosting a clump of star formation at the tip, and in that respect it resembles a system involving massive colliding galaxies, such as the Antennae (NGC 4038/39). In the study of numerous massive interacting galaxies, evidence of in situ star formation occurring in gas-rich collisional debris has been reported (Mundell et al. 2004; de Mello et al. 2008; Peterson et al. 2009). Such regions are also believed to be a nursery of super star clusters or TDGs (Duc & Mirabel 1994; Duc et al. 2007, 2014; Paudel et al. 2015, 2017). These evidences of observation are also supported by idealized and cosmological numerical simulations of galaxies, where massive and compact super star clusters are seen forming in tidal tails (Bournaud et al. 2008; Renaud et al. 2015; Ploeckinger et al. 2018) and some of them may have evolved independently and survived against internal feedback and external tidal shear. The most massive and extended of them may become independent TDGs (Wetzstein et al. 2007).

The same phenomena seem to also occur in dwarf–dwarf major mergers. We find a blue stellar clump at the tip of the stellar stream that hosts the star-forming region. It has a stellar mass of $1.9 \times 10^7 M_\odot$. As its parent galaxies are low-mass systems with shallow potential wells, one may speculate that it will survive longer than it would have in an environment of systems involving massive merging galaxies, e.g., NGC 4038/39.

In comparison, NGC 4038/39 TDG is brighter than KUG 0200-096 TDG with a $V$-band absolute magnitude of $-15.3$ mag, and it has star formation rate 0.03 $M_\odot$ yr$^{-1}$ (Mirabel et al. 1992). Currently, KUG 0200-096 TDG is forming stars at the rate of 0.02 $M_\odot$ yr$^{-1}$ and both follow a the scaling relation of SFR and blue-band absolute magnitude defined by normal galaxies, see Figure 6. Hibbard et al. (2001) presented a high-resolution HI mapping of NGC 4038/39 and its TDG Candidates. They found the HI morphology possesses plenty of tidal features and substructures. The HI tail nearly follows the extension of both antennae observed in the optical. In KUG 0200-096, we find that the gaseous tail does not overlap with the optical counterpart.
However, note that our spatial resolution is not sufficient enough to resolve the H I tail, to confirm whether it has a substructure.

The TDG H I velocity is closer to that of D1 and a careful examination of Figure 5 reveals that the extended H I emission toward the TDG actually originates in D1 (see higher velocity channel maps). It is possible that the H I tail actually emerges from D1, and that the stellar stream and the H I extension do not have the same point of origin, but are just projected on each other on sky. That can also explain the observed offset between the H I tail and the stellar stream and the lower relative line-of-sight velocity between D1 and the TDG. In this scenario, the TDG may be located at the end of the H I tail, but the location of the TDG near the tip of stellar stream may be a chance projection. Like the Antennae, KUG 0200-096 may be hosting two antennae: one being the gas poor stellar stream originated from D2 and the other, an H I tail originated from D1. In any case, to confirm this, we certainly need to study a higher-resolution and better signal-to-noise ratio HI map.

The most interesting difference between NGC 4038/39 TDG and KUG 0200-096 TDG is probably that the latter is significantly more compact compared to the former. The NGC 4038/39 system is more massive, and the TDG has a 15 kpc diameter, whereas for KUG 0200-096 the TDG diameter is 2.5 kpc. Weilbacher et al. (2018) identified multiple sub-clumps in the NGC 4038/39 TDG and detected multiple HI II regions. In that sense, KUG 0200-096 TDG is morphologically more similar to BCDs, typical xBCDs (Drinkwater & Hardy 1991), and in contrast, the morphological properties of NGC 4038/39 TDG are comparable to those of a typical dwarf irregular galaxy (dI).

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ORCID iDs
Sanjaya Paudel https://orcid.org/0000-0003-2922-6868
Suk-Jin Yoon https://orcid.org/0000-0002-1842-4325

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