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# Dark Memories of the Past: Discovery of Ultra-Diffuse Objects around NGC 1068

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**Abstract.** We have searched for a sign of the past dynamical disturbance events on NGC 1068, an archetypical Type-2 Seyfert galaxy, using deep and wide optical imaging data by the Subaru telescope. The data taken by Hyper Suprime-Cam (HSC) as well as the archived data by Suprime-Cam reveal several faint outer structures of the galaxy, most of which were never reported before. We discover three large ($r_e = 3 - 5.5$ kpc), extremely diffuse objects (UDOs) within 45 kpc from the center of NGC 1068. We suggest that two of these UDOs are actually a part of a large loop-like structure surrounding NGC 1068. Such an extremely faint loop or stream is the direct evidence for a past minor merger event. The third UDO has a distorted morphology, suggesting that it is under the influence of strong tidal field. Furthermore, we have identified another ultra-diffuse but compact ($\mu_{0,r} > 25$ mag arcsec$^{-2}$, r$_e \sim 0.8$kpc ) dwarf galaxy within ~140 kpc from NGC 1068. We speculate that this ultra-diffuse dwarf could be the object related to the ancient tidal disruption event (tidal dwarf) during the early mass assembly period of NGC 1068. We also detect an asymmetric outer one-arm structure emanated from the western edge of the outermost disk of NGC 1068 together with a ripple-like structure at the opposite side. These structures are also expected to arise in a late phase (up to several billion years ago) of a minor merger, according to numerical simulations. Our findings are consistent with the idea that the AGN activity in NGC 1068 is caused by a past minor merger.

**Keywords.** galaxies: dwarf, galaxies: interaction, galaxies: individual (NGC 1068)

## 1. Introduction

NGC 1068 is one of the nearest (~15 Mpc) galaxies with a powerful Seyfert-2 AGN. Thanks to the rich observational data available for NGC 1068, it has been playing the key role as the "touchstone" to test the hypotheses of the AGN-triggering mechanism and the unified models of AGNs.

There are two major hypotheses on the origin of Seyfert AGN. The one is the internal secular process where the galactic disk generates the non-axisymmetric structure (e.g., bars) which efficiently removes the angular momentum of the circulating gas to dump it to the center. NGC 1068 indeed has the bar structure in the center. However, it is also known that the axis of the dust torus around the central Supermassive Blackhole (SMBH) of NGC 1068 is nearly perpendicular to the rotation axis of the galactic disk. It is not easy to explain this by a simple secular evolution scenarios.

The other hypothesis attributes the origin to the external perturbation. For bright AGNs such as QSOs, it is widely accepted that the major merger has played the key role for triggering the activity (e.g., Sanders *et al.* 1988). On the other hand, the situation is not clear for weaker AGNs. Many Seyfert galaxies indeed appear to be ordinary-looking spiral galaxies (e.g., Malkan *et al.* 1998). NGC 1068 is also a beautifully-symmetric spiral galaxy without any morphological disturbance (de Vaucouleurs *et al.* 1991).

Taniguchi (1999) proposed an AGN unification model by mergers. They discussed that all Seyfert AGN activities were triggered by the minor merger of the nucleated (= with the SMBH at its center) satellite galaxy. When a satellite is merged to the main galaxy, most of its body will be destroyed by the tidal field of the host. However, if it is nucleated, its core with a SMBH can survive and go into the center of the main galaxy until they merge. The gas near the center of the galaxy can violently be disturbed throughout the coalescence process, which may eventually trigger the starburst and the AGN activity. The rotation axis of the dusty torus around the SMBH is mainly determined by the orbit of the sinking satellite (which is random), so its rotation axis is not necessarily aligned with the disk axis of the host galaxy.

To test the idea of the External Trigger for Seyfert galaxies, we want to detect the sign of the past minor merger. It might still remain at the very outer part of the host galaxy due to its longer dynamical timescale. Thus, we did a very deep imaging observation for NGC 1068 aiming for the detection of the possible signature of the past minor merger which was never reported before.

In this work we use 15.9 Mpc as the distance toward NGC 1068 (Kormendy & Ho 2013; $m - M = 31.01$ and 1" = 0.077 kpc). The magnitude is in the AB system.

## 2. Observation and Data

The data for present analysis were taken by Hyper Suprime-Cam (hereafter HSC; Miyazaki *et al.* 2018) and Suprime-Cam (Miyazaki *et al.* 2002) on the 8.2 m Subaru Telescope. We gathered 2800 sec exposures for HSC in $r2$ filter (basically the same as the SDSS $r$ filter) in 2016, while the $R_c$-band Suprime-Cam data was downloaded from the Subaru public archive (SMOKA). We refer to Tanaka, Yagi & Taniguchi (2017) about the detail of the reduction and the quality of these data.

The field around NGC 1068 is included in the the Sloan Digital Sky Survey (hereafter SDSS) Stripe 82 deep field (Annis *et al.* 2014). We also use the data to get the color information of our discovered features.

We have discovered a number of intriguing, extremely-faint features around NGC 1068 as shown in Figure 1, most of which were never reported before. Firstly, we find three very large and ultra-diffuse objects (UDOs) lying close vicinity of the NGC 1068 within the projected distances of 45 kpc from the center (middle panel of Fig. 1). Hereafter, we call them UDO-SW, UDO-NE, and UDO-SE where UDO = Ultra Diffuse Object, SW = south west, NE = north west, and SE = south east; note that UDO-SE was already found in the SDSS Stripe 82 data (Bakos & Trujillo 2012).

We also find another UDO-like object that is 2 magnitudes fainter and smaller by a factor of 3 to 5 than those of the three UDOs ('LSB-FSW' in Fig. 1). This object may belong to a class of low surface brightness galaxy. This object is located along the line connecting UDO-NE and UDO-SW. We speculate that the object might be related to the past interaction event that formed the loop by UDO-NE and UDO-SW (see later); these three ultra-diffuse objects might have a possible physical connection.

We measure the structural parameters of these UDOs and others shown in Fig. 1 using the GALFIT code (Peng *et al.* 2010). The effective radius of these UDOs are all larger than 2.5 kpc. The central surface brightness of them ranges from 26.4 (UDO-SE) to 27.0 (UDO-SW and UDO-NE) mag arcsec$^{-2}$. These values are even more extreme than the

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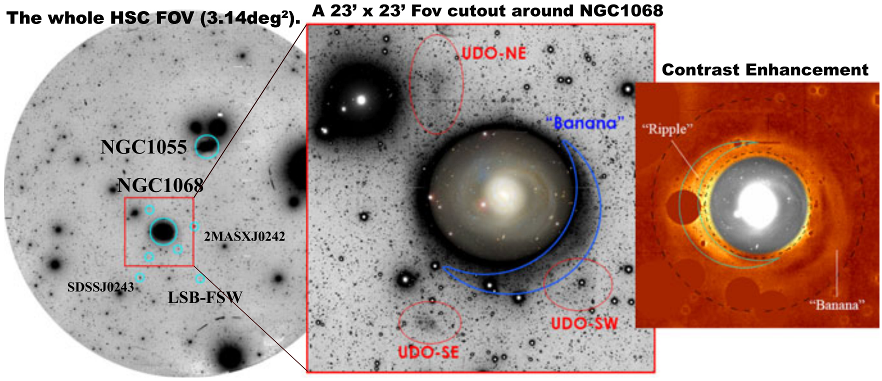


**Figure 1.** Left: the position of the UDOs (see text) and dwarfs near NGC 1068. Middle: Zoom-in view around NGC 1068. Right: the contrast-enhanced image of the NGC 1068 disk, showing the faint outer structures. The scale of middle and right images are the same.

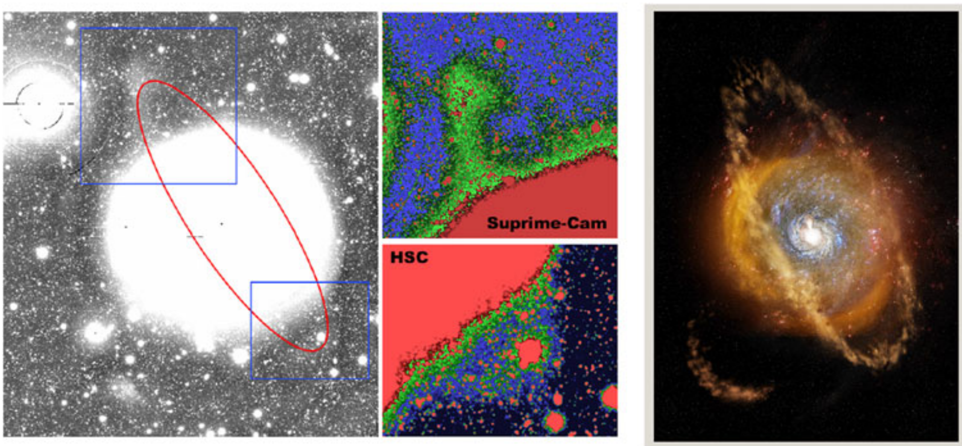


**Figure 2.** Left: The morphology of UDOs in contrast-enhanced images show a hint of the loop-like structure as shown in red oval. Right: The artist's impression on NGC 1068 (Credit: Akihiro Ikeshita).

Ultra-Diffuse Galaxies discovered predominantly in cluster environment (van Dokkum *et al.* 2015); namely they are too big for its faintness. The measured Sérsic index for these objects is less than 0.3, which is also unusually small.

The morphology of both UDO-NE and UDO-SW indicates that they might actually be a part of the loop-like structure.UDO-NE and UDO-SW indeed locate contralaterally with respect to NGC 1068. These facts lead us to speculate that they are actually a part of single loop structure, as demonstrated in Figure 2. We estimate that the orbital timescale of the loop is $\sim 1.2$ Gyr, which suggest that the minor merger event responsible for the loop would be as old as 4 Gyrs (Tanaka *et al.* 2017).

The object UDO-SE shares the similar unusual properties to the UDO-SW and UDO-NE. The morphology seen in the middle panel of Fig. 1 shows some distortion toward the lower-right, though we do not see any further extension or hint of tidal feature around the object. We speculate that UDO-SE might be a tidal dwarf galaxy which were once the densest part of a tidal stream which are already scattered away (e.g., Duc *et al.* 2014).

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Another newly-discovered feature is an asymmetric outer one-arm structure emanated from the western edge of the outermost disk of NGC 1068 together with a ripple-like structure at the opposite side. They are barely seen in the contrast-enhanced image of the NGC 1068 disk, as shown in the right panel of Figure 1. These structures are expected to arise in a late phase of a minor merger according to published numerical simulations of minor mergers (Kazantzidis *et al.* 2008, Purcell *et al.* 2011). All these lines of evidence suggest that NGC 1068 experienced a minor merger several billions years ago.

To check the consistency of the scenario, we measure the color of these very diffuse feature using the Stripe 82 data of the SDSS ($g$, $r$, & $i$ are used here). The Stripe 82 data is much deeper ($> 2$ mag) than the usual SDSS scan (Schawinski *et al.* 2010). We have identified these UDOs in the data, and have measured the $g-r$ & $r-i$ color of them. We find that they all have similar colors ($g-r=0.8\pm0.1$ & $r-i=0.4\pm0.2$), which is consistent with the G-type stellar population (see Fukugita *et al.* 2011 for the stellar colors in $gri$ color plane). This suggests that they might have halted the star formation several Gyrs ago, consistent with their past minor-merger origin.

In the end, we briefly discuss the minor-merger-driven triggering of nuclear activity in the case of NGC 1068. According to the hypothesis by Taniguchi (1999), the current AGN activity of NGC 1068 would be caused by a past minor merger of the nucleated dwarf. If this is the case, there should be a sign of a minor merger that has happened some Gyrs ago. We have shown that NGC 1068 is indeed rich in such structures. The color of these features are consistent with the idea that they are the fossil of the past minor merger event that has led to trigger the AGN activity. Our study demonstrates that the faint outer structure and companion dwarfs can act as the clue to investigate the triggering mechanism of Seyfert-type AGNs. The future systematic deep survey for nearby Seyfert galaxies by Subaru will shed light on the triggering mechanism for such weak AGNs (Takahashi *et al.* in prep).

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