A New Metal-poor Globular Cluster and Resolved Stars in the Outer Disk of the Black Eye Galaxy M64: Implication for the Origin of the Type III Disk Break

Jisu Kang1, Yoo Jung Kim1, Myung Gyoon Lee1, and In Sung Jang2

1 Astronomy Program, Department of Physics and Astronomy, Seoul National University, 1 Gwanak-ro, Gwanak-gu, Seoul 08826, Republic of Korea
2 Leibniz-Institut für Astrophysik Potsdam (AIP), An der Sternwarte 16, 14482 Potsdam, Germany

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Abstract

M64 is a nearby spiral galaxy with a Type III antitruncation component. To trace the origin of the Type III component, we present Hubble Space Telescope/Advanced Camera for Surveys (ACS) F606W/F814W photometry of resolved stars in a field located in the outer disk (2.5 \( \lesssim r \lesssim 6.5 \)) of M64. At \( r \approx 5.5 \) (7 kpc) to the east, we discover a new metal-poor globular cluster (\( R_{\text{eff}} = 5.73 \pm 0.02 \) pc and \( M_V = -9.54 \pm 0.09 \) mag), M64-GC1. This is the first globular cluster found in M64. The color–magnitude diagram (CMD) of the resolved stars in M64-GC1 is well matched by 12 Gyr isochrones with \( \text{[Fe/H]} = -1.5 \pm 0.2 \), showing that this cluster belongs to a halo. The CMD of the resolved stars in the entire ACS field shows two distinguishable red giant branches (RGBs): a curved metal-rich RGB and a vertical metal-poor RGB. The metal-rich RGB represents an old metal-rich ([Fe/H] \( \approx -0.4 \)) disk population. In contrast, the CMD of the metal-poor RGB stars is very similar to the CMD of M64-GC1, showing that the metal-poor RGB represents a halo population. The radial number-density profile of the metal-rich RGB stars is described by an exponential disk law, while the profile of the metal-poor RGB stars is described by a de Vaucouleurs’s law. From these, we conclude that the origin of the Type III component in M64 is a halo that has a much lower metallicity than the disk or bulge population.

Unified Astronomy Thesaurus concepts: Galaxy stellar content (621); Spiral galaxies (1560); Globular star clusters (656); Galaxy stellar halos (598); Galaxy disks (589); Galaxy distances (590)

1. Introduction

M64 (NGC 4826) is an early-type spiral galaxy ((R)SA(rs)ab) with the nicknames Black Eye Galaxy, Evil Eye Galaxy, and Sleeping Beauty Galaxy, due to its prominent dust lane around the bright bulge. The basic properties of M64 are listed in Table 1.

M64 shows several interesting features. First, it is an isolated galaxy located in the low-density environment. It used to be known to have only one known companion dwarf galaxy, NGC 4789A (\( M_B = -14 \) mag) (Jacobs et al. 2009). Although several dwarf galaxies, including Coma P (\( M_B = -10 \) mag), were recently suggested to be other companions of M64 (Brunker et al. 2019), it can be still considered an isolated galaxy. Second, it hosts two counterrotating gas rings: the inner gas ring (\( r < 1' \)) follows the galaxy rotation, while the outer gas ring rotates in the opposite direction (Braun et al. 1992). The outer ring is considered to be a remnant of a recent merger with a gas-rich satellite (Braun et al. 1992, 1994; Rubin 1994; Walterbos et al. 1994; Rix et al. 1995; Watkins et al. 2016). Third, recent star formation is concentrated only in the inner disk region at \( r < 200' \), while the H\( \alpha \) distribution is much more extended (out to \( r \approx 600' \), Watkins et al. 2016).

Another interesting feature of M64 is that its disk is composed of three substructures. From the recent deep \( BV \) surface photometry, Watkins et al. (2016) found that the surface-brightness profiles of M64 can be divided into three parts: (1) an inner disk, (2) an outer disk, and (3) a Type III antitruncation (upbending) component. In the inner disk region at \( r < 200' \), spiral arms and evidence of recent star formation are seen. We can notice dust lanes, young stars, strong UV emission, and a high density of H\( \alpha \) gas from the multiband images of M64 (see Figure 3 of Watkins et al. 2016). The recent star formation in the inner disk is believed to be due to a merger with a gas-rich dwarf galaxy (Braun et al. 1994; Watkins et al. 2016). In the outer disk region at \( 200' < r < 400' \), no spiral arms or evidence of recent star formation are seen. Its color is red, indicating that the disk stars may be old and metal rich (Watkins et al. 2016). Outside the outer disk at \( 400' < r < 900' \), the Type III antitruncation component is located. It is an upbending structure following a break at \( r \approx 400' \) in the surface-brightness profiles of M64. Its surface brightness is as low as \( \mu_B > 27 \) mag arcsec\(^{-2} \).

While the origins of the inner and outer disks are quite clear, the origin of the Type III break is still mysterious. According to Watkins et al. (2016), the origin of the Type III component in M64 can be explained by three scenarios. First, it can be originated from disk stars that migrated from the inner region. This possibility is supported by the \( (B − V) \) color of the Type III component stars, which is as red as that of the outer disk stars. However, the uncertainty of the color measurement for \( r > 400' \) is significant because of its low surface brightness. Moreover, it is difficult for disk stars to migrate such a large distance (several disk scale lengths beyond the spiral features). Second, the Type III component can be originated from star formation in extended gas induced by counterrotating kinematics of M64. If so, the \( (B − V) \) color of the Type III component stars may be much bluer (younger) than previously known. Third, it can be originated from halo stars. If so, the stars in this component must be old and metal poor.

Photometry of resolved stars located in the low surface-brightness region of a galaxy is an excellent tool to study the nature of diffuse galaxy light in terms of stellar populations and to trace the origin of the stellar populations. In this study, we explore the origin of the Type III break using the photometry of resolved stars in an outer disk field of M64 based on the Hubble Space Telescope (HST)/Advanced Camera for Surveys.
(ACS) images. To date, little is known about the resolved stars or star clusters in M64. We adopt the distance to M64, 4.33 Mpc as determined later in this study. The foreground reddening toward M64 is as low as $E(B - V) = 0.037$ ($A_{F606W} = 0.102$ and $A_{F814W} = 0.063$, Schlafly & Finkbeiner 2011).

This paper is organized as follows. Section 2 describes data used in this study and how we reduce and analyze the data. In Section 3, we present main results: a discovery of a new globular cluster, color–magnitude diagrams (CMDs) of the resolved field stars, an estimation of the tip of the red giant branch (TRGB) distance, and radial number-density profiles of the resolved stars. Implications of our results are discussed in Section 4. Finally, we summarize our results and give a conclusion.

### 2. Data and Data Reduction

We used archival data of HST/ACS F606W/F814W images of M64 (PI: Tully, PID: 10905). We combined individual flic (charge transfer efficiency corrected) frames of each filter using DrizzlePac (Gonzaga et al. 2012). The total exposure times are 922 s for F606W and 1128 s for F814W. The final image scale is $0.05$ arcsec per pixel.

In Figure 1, the location of the HST/ACS field is marked on the Sloan Digital Sky Survey (SDSS) color image of M64. The ACS field is positioned at $r = 2.3$–$6.2$ arcsec along the eastern major axis from the center of M64. Here, $r$ is the galactocentric distance and $a$ is the projected galactocentric distance. Note that the galaxy light of the SDSS image is clearly seen in the western chip of the ACS, while it is barely seen in the eastern chip.

For the detection and photometry of the point sources in the images, we utilized DOLPHOT (Dolphin 2000). The drizzled F814W image was used as a reference image, and the individual flic images were used as input images. We used the DOLPHOT input parameters listed in Table A2 of Monachesi et al. (2016), which were used for the photometry of Galaxy Halos, Outer disks, Substructure, Thick disks, and Star clusters (GHOSTS) fields. We applied selection criteria for the stars similar to those used in the GHOSTS survey (Radburn-Smith et al. 2011): $-0.06 < SHARP_{F606W} + SHARP_{F814W} < 1.30$, CROWD$_{F606W} +$ CROWD$_{F814W} < 1.0$, $S/SHARP_{F606W,F814W} > 5$, type$_{F606W,F814W} = 1$, flag$_{F606W,F814W} < 2$. We increased the maximum crowding parameter from 0.16 to 1.0, considering the crowding of the M64 field. We use the Vega magnitude system following the DOLPHOT output parameters. Aperture corrections were automatically applied by DOLPHOT routine ($Apcor = 1$). The systematic errors of aperture corrections are on average $\pm 0.03$ mag (Monachesi et al. 2016).

Artificial star tests were also carried out using the DOLPHOT routine fakelist to generate the star lists. We generated 1000 artificial stars with a magnitude range of 23.5 $< F606W < 27.5$ and a color range of 0.5 $< (F606W - F814W) < 3.0$, and reran DOLPHOT with FakeStar parameters (FakeMatch = 3, FakePSF = 2, FakeStarPSF = 1, RandomFake = 1, FakePad = 0). We repeated this procedure 100 times to generate a total of 100,000 artificial stars. Figure 2 shows the recovery fraction of the bright stars along the radial bin according to the two different magnitude ranges (24.0 $\leq F814W < 24.4$, 24.4 $\leq F814W < 24.8$). The recovery fraction decreases with decreasing projected galactocentric distance $a$, but it is higher than 50% even at the innermost region. This result was used to correct the radial number-density profile of the red giant branch (RGB) stars in Section 3.4.
3. Results

3.1. Discovery of a New Resolved Globular Cluster

From the visual inspection of the ACS images, we discovered a new globular cluster, henceforth named M64-GC1, located at $\theta_r = 5.5$ in the east. This is the first globular cluster found in M64, and it is the only star cluster with resolved stars we could find in the images. The position of M64-GC1 is marked by a circle in Figure 1. This cluster is seen as a bluish point source in the SDSS color image. Figure 3 is a pseudo color map of the zoomed-in HST/ACS image for M64-GC1. This new cluster shows a very round shape and its outer region is partially resolved into individual stars, which verifies that it is indeed a star cluster.

We derived the radial number-density profile of the resolved stars by counting the detected stars with $F814W < 26.5$ mag in the cluster region at $R_{GC} < 1''2$, due to severe crowding. However, the radial profile clearly shows an excess at $1''2 < R_{GC} < 2''7$ and a flat distribution in the outer region at $R_{GC} > 4''$. This shows that most detected stars at $1''2 < R_{GC} < 2''7$ are the members of the cluster.

In the left panel of Figure 5 we display the CMD of the resolved stars in M64-GC1. We plotted the stars at $1''2 < R_{GC} < 2''7$, most of which are considered to be cluster members, by magenta circles. Then we plotted the stars in the outer background region at $4''0 < R_{GC} < 7''0$, which must be background sources outside the cluster, by pale blue circles. The area of the outer background region is about six times larger than that of the central cluster region. For comparison, we overlaid PARSEC isochrones (Bressan et al. 2012) for ages of 12 Gyr and [Fe/H] = −2.2 to 0.0 with a step of 0.2 dex (green lines). These isochrones are shifted according to the distance $(m - M)_0 = 28.2$ and foreground reddening $A_{F506W} = 0.102$ and $A_{F814W} = 0.063$ of M64 (Schlafly & Finkbeiner 2011).

In the CMD, most stars in the cluster region are located along a vertical branch at $(F606W - F814W) \approx 1.0$, which is consistent with RGB isochrones with low metallicity, [Fe/H] $\sim -1.5$. In contrast, the stars in the background region are seen...
along curved branches with much redder colors. Therefore, the stars in the cluster region must be mostly the members of the new metal-poor globular cluster. We estimate the mean metallicity of the cluster, from the comparison of these RGB stars with 12 Gyr isochrones, obtaining [Fe/H] = −1.5 ± 0.2. This shows that M64-GC1 is indeed an old metal-poor globular cluster belonging to the halo population.

For comparison, we display the CMD of the resolved stars in Coma P, a new dwarf companion of M64, in the right panel of Figure 5. Brunker et al. (2019) presented F606W/F814W photometry of the resolve stars in Coma P. To obtain the CMD of the resolved stars in Coma P, we applied a similar reduction and photometry process for the HST/ACS F606W/F814W images of Coma P (PI: Salzer, PID: 14108) as used for M64 images. The CMD of Coma P we obtained is consistent with the result of Brunker et al. (2019). The same isochrones are overlayed after a shift according to the distance (m − M)_0 = 28.7 and foreground reddening (A_{F606W} = 0.077 and A_{F814W} = 0.048) of Coma P given by Brunker et al. (2019). Unlike the RGB stars in M64-GC1, the RGB stars of Coma P show a much broader color (metallicity) distribution with a slightly higher mean metallicity, [Fe/H] ≈ −0.9. Indeed, M64-GC1 has a lower metallicity than Coma P. Moreover, there are a dozen young stars located at (F606W − F814W) ≈ 0 in the CMD of Coma P, which are not seen in the CMD of M64-GC1.

We estimate the total integrated magnitude and effective radius of M64-GC1 from surface photometry using IRAF/ELLIPSE task on the ACS images (Jedrzejewski 1987). Figures 6(a) and (b) display the surface brightness and color profiles of M64-GC1. We fit the surface-brightness profiles of the cluster with a King profile (King 1962), as shown by dotted lines in Figure 6(a). We derive core radius r_c = 0′.13 ± 0′.01 (2.7 ± 0.2 pc) and tidal radius r_t = 2′.59 ± 0′.02 (54.4 ± 0.4 pc) in F814W images, and r_c = 0′.12 ± 0′.01 (2.5 ± 0.2 pc) and r_t = 2′.64 ± 0′.02 (55.4 ± 0.4 pc) in F606W images. These values are obtained after correcting the point-spread function effect. The color profile is almost constant with (F606W − F814W) ≈ 0.7 to 0.8 at R_GC < 1′.5.

The integrated magnitude and color profiles of the cluster are shown in Figures 6(c) and (d). From this we derive the total magnitude of the cluster, F606W(GC1) = 18.5 mag, and F814W(GC1) = 17.8 mag. We also fit the Sérsic profile to the M64-GC1 image using GALFIT (Peng et al. 2010). From this we derive the total magnitude of the cluster, F606W(GC1) = 18.53 ± 0.01 mag, and F814W(GC1) = 17.80 ± 0.01 mag (corresponding to the Johnson Cousins system magnitudes after foreground extinction correction, V_0 = 18.64 ± 0.03 mag and I_0 = 17.72 ± 0.02 mag; Sirianni et al. 2005), and the effective radius of R_eff = 0′.273 ± 0′.001 (5.73 ± 0.02 pc). These results agree very well with those from the IRAF/ELLIPSE task. Adopting the distance to M64, we obtain absolute integrated magnitudes of the cluster, M_{F606W(GC1)} = −9.75 ± 0.09 mag, and M_{F814W(GC1)} = −10.44 ± 0.09 mag (corresponding to the Johnson Cousins system magnitudes M_V = −9.54 ± 0.09 mag and M_I = −10.46 ± 0.09 mag). In Table 2 we list the basic information of M64-GC1 derived in this study.

3.2. CMDs of the Resolved Field Stars

For the following analysis we divided the entire ACS field into two regions: an inner region at a < a_{25,B} = 5′.0 (6.3 kpc) and an outer region at a ≥ a_{25,B}. Here, a_{25,B} is the projected galactocentric distance at which the B-band surface brightness is 25 mag arcsec^{-2}. a_{25,B} is shown by a large ellipse in Figure 1. In Figure 7 we display the CMDs of the resolved stars in the inner and outer regions. It is found that the resolved stars are mostly RGB stars with a large range of color.

The most notable feature in the CMDs is that there are two distinguishable RGBs in the bright magnitudes with F814W ≤ 25.0: one is a vertical blue branch at (F606W − F814W) ≈ 1.0, and the other is a curved red branch with a wide range of color reaching (F606W − F814W) ≤ 2.5. The vertical RGB
represents a metal-poor RGB, and the curved RGB denotes a metal-rich RGB. The presence of these two branches is more clearly seen in the outer region than in the inner region. The inner region is dominated by the metal-rich RGB stars, while the contribution from the metal-rich RGB stars and metal-poor RGB stars are comparable in the outer region.

The metal-poor RGB in the CMDs is very similar to the RGB of the new globular cluster M64-GC1, showing that the metal-poor RGB and the metal-rich RGB are clearly separated in the bright magnitudes. They are merged into one as the stars get fainter so it is difficult to

3.3. TRGB Distance Estimation

We estimate a distance to M64 using the TRGB method (Lee et al. 1993) to a sample of metal-poor RGB stars in the outer region of the ACS field. Crowding is much less, and the contribution of halo stars is larger in the outer region than in the inner region. Figure 8(a) is the CMD of the resolved stars in the outer region of M64 which is already shown in Figure 7(b). The shaded gray region represents the metal-poor RGB stars in the outer region which were used to estimate the TRGB magnitude.

Figure 8(b) shows the luminosity function of the stars within the shaded gray region in the CMD. Applying the Sobel filter method described in Jing & Lee (2017) to the luminosity function of the stars, we derive a TRGB magnitude, $M_{F814W_{TRGB}} = 24.21 \pm 0.03$ mag. This TRGB magnitude does not change much with the choice of Sobel filters. For example, the edge-detection algorithm used in Freedman et al. (2019), employing the Gaussian-windowed, locally weighted scatterplot smoothing, gives the TRGB magnitude of $M_{F814W_{TRGB}} = 24.22 \pm 0.02$ (ran) $\pm 0.01$ (sys) mag with the optimal smoothing scale of $\sigma = 0.08$ mag. The weighted-edge-detection filter suggested by Mage et al. (2008) measures $M_{F814W_{TRGB}} = 24.21 \pm 0.04$ mag, which is also consistent within uncertainties. Adopting the TRGB calibration in Jing & Lee (2017) (for metal-poor RGB, $M_{F814W_{TRGB}} = -4.03 \pm 0.07$), the foreground reddening in Schlafly & Finkbeiner (2011) ($A_{F814W} = 0.063$), and the aperture correction error of 0.03 mag, we obtain a distance modulus, $(m-M)_0 = 28.18 \pm 0.03$ (ran) $\pm 0.08$ (sys) (corresponding to a distance of 4.33 $\pm$ 0.18 Mpc).

3.4. Radial Distribution of the Metal-poor and Metal-rich RGB Stars

In the CMDs of Figure 7, the metal-poor RGB and the metal-rich RGB are clearly separated in the bright magnitudes. They are merged into one as the stars get fainter so it is difficult to
separate them in the faint magnitudes. For the following analysis, we selected bright metal-poor RGB stars and metal-rich RGB stars with $F814W < 24.8$ mag using the boundaries marked by blue and red boxes in Figure 7.

We derive the radial number-density profiles of the selected metal-poor RGB stars and metal-rich RGB stars, as well as all bright RGB stars with $24.1 < F814W < 24.8$ mag, and show them in Figure 9. This result was corrected by the artificial star tests (see Figure 2). For comparison, we also plot the schematic surface-brightness profiles of galaxy light given by Watkins et al. (2016), showing the inner/outer disk and the Type III antitruncation component. We converted the schematic surface-brightness profiles to be consistent with the unit of the number-density profiles, $\mu_B$ divided by 2.5, and shifted them vertically to match roughly the number-density profile at $a \approx 400''$.

Several features are noted in Figure 9. First, the radial number-density profile of the metal-rich RGB stars is much steeper than that of the metal-poor RGB stars in the same range. The flattening or decrease of the radial number-density profiles in the innermost bins at $a < 3'$ are mainly due to incompleteness of our photometry, although we corrected the incompleteness with the result of artificial star tests. Second, the slope of the radial number-density profile of the metal-rich RGB stars is consistent with that of the surface-brightness profile for the outer disk. Third, the slope of the radial number-density profiles of all bright RGB stars is similar to that of the surface-brightness profile for the outer disk. Fourth, the radial number-density profile of the metal-poor RGB stars is slightly steeper than, but roughly consistent with, that of the surface brightness profile for the Type III component given by Watkins et al. (2016).

We fit the radial number-density profiles for $3' \lesssim a \lesssim 6'$ with a Sérsic function (Sérsic 1963), obtaining $n = 0.61 \pm 0.03$ ($a_{\text{eff}} = 2'22 \pm 0.05$) for all bright stars, $n = 0.39 \pm 0.02$ ($a_{\text{eff}} = 2'54 \pm 0.04$) for the metal-rich RGB stars, and $n = 3.79 \pm 0.39$ ($a_{\text{eff}} = 0'87 \pm 0.10$) for the metal-poor RGB stars. Thus, the radial number-density profile of the metal-rich RGB stars follows an exponential disk law, while that of the metal-poor RGB stars is described well by a de Vaucouleurs $r^{1/4}$ law.

4. Discussion

4.1. M64-GC1 in Comparison with Other Globular Clusters

It is easy to spot M64-GC1 in the ACS images because it is relatively bright and its outer region is partially resolved into...
individual stars. However, it is the only globular cluster we could find in the ACS field. This implies that the total number of globular clusters in M64 is small and/or M64-GC1 may be unusually brighter than the other globular clusters in this galaxy.

In Figure 10 we compare the effective radius and total magnitude of M64-GC1 with those of globular clusters in other galaxies in the literature (the Milky Way (Harris 1996, 2010), M31 (Peacock et al. 2010), and M81 (Nantais et al. 2011)) and two intragroup globular clusters (IGGCs) in the M81 group (Jang et al. 2012). We also plotted a boundary separating normal and extended globular clusters suggested by van den Bergh & Mackey (2004); \( \log(R_{\text{eff}}) = 0.2M_V + 2.6 \). M64-GC1, as well as M54 (NGC 6715), \( \omega \) Centauri (NGC 5139), and IGGCs, is above the boundary line. This shows that M64-GC1 belongs to the brightest and largest globular clusters. M54 and \( \omega \) Centauri are often considered to be core remnants of disrupted dwarf galaxies (Zinnecker et al. 1988; Freeman 1993; Sarajedini & Layden 1995). Therefore, M64-GC1 is also a possible core remnant of a tidally disrupted dwarf satellite around M64.

### 4.2. Comparison of Distance Estimation

The previous TRGB distance estimates for M64 show a significant variation from \( (m - M)_0 = 28.2 \) to 28.6, as summarized in Table 3 (Mould & Sakai 2008; Jacobs et al. 2009; Tully et al. 2013, 2016, and the Extragalactic Distance Database (EDD)). The previous surface-brightness fluctuation (SBF) distance values show an even larger difference: \( (m - M)_0 = 29.37 \pm 0.20 \) in Tonry et al. (2001) and \( (m - M)_0 = 28.60 \pm 0.08 \) in Tully et al. (2013). Note that Watkins et al. (2016) adopted a distance 4.7 Mpc given in Jacobs et al. (2009), while Brunker et al. (2019) adopted a distance 5.3 Mpc given in Tully et al. (2016).

We obtain a distance to M64 applying the TRGB method to the photometry of metal-poor RGB stars in the outer region, \( (m - M)_0 = 28.18 \pm 0.09 \) (4.33 \pm 0.18 Mpc). This value is 0.4 mag smaller than those in Mould & Sakai (2008) and Tully et al. (2013, 2016), but it is very similar to the one in EDD, \( (m - M)_0 = 28.22 \pm 0.02 \).

Note that the F814W TRGB magnitude in this study, \( F814W_{\text{TRGB,0}} = 24.15 \pm 0.03 \), is 0.5 mag brighter than the value in Mould & Sakai (2008), 24.64 mag. We used only the metal-poor RGB stars in the outer region, while the estimation of Mould & Sakai (2008)—as well as those in Tully et al. (2013) and Tully et al. (2016)—might have been based mainly on all RGB stars. If we determine the TRGB magnitude using all RGB stars, we obtain \( F814W_{\text{TRGB,0}} \approx 24.5 \) mag, which is similar to those obtained by Mould & Sakai (2008) and Jacobs et al. (2009), and probably Tully et al. (2013, 2016) as well. EDD provided a value of \( F814W_{\text{TRGB,0}} = 24.26 \pm 0.02 \), which is 0.1 mag fainter than ours and presented a similar distance value. If we determine the TRGB magnitude using metal-poor RGB stars in the entire region, we obtain \( F814W_{\text{TRGB,0}} \approx 24.25 \), which is similar to the value provided by EDD. However, they used all RGB stars in the entire region without any color selection (D. Makarov 2020, private communication). Then it is difficult to explain the 0.1 mag difference.

### 4.3. The Origin of the Type III Component in M64

Erwin et al. (2005, 2008) and Pohlen & Trujillo (2006) introduced the classification of Type III breaks into two types according to the shape of outer isophotes: IIId for disk components
and IIIIs for spheroidal components. In the case of IIIIs breaks, the isophotes in the outer region become progressively rounder than those in the inner region. They described the spheroidal component in IIIIs breaks is either the outer extent of the bulge or a separate stellar halo.

From the surface photometry of M64, Gutiérrez et al. (2011) classified it as IIIIs, noting that there is a disk break at $r \approx 370''$ and that the ellipticity of the isophotes decreases abruptly beyond $r \approx 340''$. Watkins et al. (2016) also found a disk break at $r \approx 400''$ and inferred that the Type III antitruncation component in M64 may be due to the spheroidal halo, noting that the isophotes of the outer region of M64 are round and that it is difficult to build outer disks with current models.

We find that the resolved RGB stars in the ACS field are composed of two main stellar populations: metal-poor RGB stars and metal-rich RGB stars. The radial number-density profile of the metal-rich RGB stars is described by an exponential disk law, while that of the metal-poor RGB stars is fit well by a Sérsic law with $n \approx 4$. In the CMDs, the metal-poor RGB is very similar to the RGB of the new halo globular cluster (M64-GC1).

These results show that the metal-poor RGB represents a low metallicity ([Fe/H] $\approx -1.5$) halo population, while the metal-rich RGB denotes a disk population with much higher metallicity ([Fe/H] $\approx -0.4$). The disk is dominated by the metal-rich RGB stars, and no clear sign of young stars is found in the ACS field. Thus, the color of the outer disk is dominated by the contribution of the metal-rich RGB stars. This is consistent with the result found in Watkins et al. (2016) that the outer disk is red and featureless. The outer region is occupied mainly by the metal-poor RGB stars. Thus, the origin of the Type III antitruncation component in the outer region of M64 is a halo, neither a disk population nor a bulge population.

### 4.4. The Origin of the Halo in M64

M64 is an isolated galaxy located in a low-density environment (see Figure 10 in Brunker et al. 2019). In such an environment, there might have been few satellites which merged and enlarged the halo of M64. This implies that the size and mass of the halo in M64 might have not been changed much since its formation, or that the accretion of dwarf galaxies into M64 was finished long ago. Thus, the halo in M64 may be pristine, as dwarf galaxies or globular clusters which have much lower mass than M64. This is consistent with our finding that the metallicity of the metal-poor RGB stars in the ACS field is as low as that of the new halo globular cluster (M64-GC1). The metallicity of the metal-poor RGB stars is much lower than that of the metal-rich RGB stars so the origin of the metal-poor RGB stars cannot be a disk or a bulge.

### 4.5. Relation Between M64 and Coma P

Coma P (AGC 229385) is an H-I-dominated blue dwarf galaxy ($M(H I) = 3.48 \times 10^7 M_{\odot}$, $M_8 = 4.3 \times 10^8 M_{\odot}$) located close (5.86") to M64 in the sky (Brunker et al. 2019). Brunker et al. (2019) measured a TRGB magnitude of Coma P from HST/ACS F660W/F814W images to be $M_8 = 24.64 \pm 0.09$ (from maximum likelihood method) or $24.60$ (from Sobel filters), and presented a distance to Coma P, $d = 5.2^{+0.28}_{-0.53}$ Mpc ($D = 28.80^{+0.11}_{-0.27}$). This value is much smaller than the previous distance estimates for Coma P, 11 Mpc based on the TRGB method (Anand et al. 2018) and 25 Mpc based on the flow model (Janowiecki et al. 2015). Brunker et al. (2019) discussed the comparison of their distance estimate with those in Janowiecki et al. (2015) and Anand et al. (2018), and concluded that their estimate is more reliable than the others.

Brunker et al. (2019) discussed the relation between Coma P and M64, adopting a distance to M64 from Cosmicflows-3 in Tully et al. (2016), ($m - M_0 = 28.62 \pm 0.15$ ($d = 5.3 \pm 0.4$ Mpc). The spatial distance between the two galaxies is as small as 590 kpc for their adopted distances. However, the relative line-of-sight velocity between Coma P ($v_{\text{helio}} = 1348$ km s$^{-1}$) and M64 ($v_{\text{helio}} = 410$ km s$^{-1}$) is as large as 938 km s$^{-1}$. Noting this large relative velocity, Brunker et al. (2019) suggested another scenario for the presence of counterrotating gas in M64 in relation with Coma P: a gas-rich progenitor of Coma P had a high speed ($v \approx 1000$ km s$^{-1}$ $\approx 1$ Mpc Gyr$^{-1}$) flyby interaction with M64 approximately 1 Gyr ago, and some of the gas stripped from Coma P resulted in the counterrotating gas ring in the outer disk of M64.

If the TRGB distance to M64 derived in this study is adopted, then the relative line-of-sight distance between Coma P and M64 increases from 200 kpc to 1.2 Mpc (corresponding to the spatial distance from 590 kpc to 1.3 Mpc). It would have taken about 1 Gyr if Coma P had an encounter with M64, and is receding with $v \approx 1000$ km s$^{-1}$ until today. Therefore, the encounter epoch is around 1 Gyr ago, which is in agreement with the scenario suggested by Brunker et al. (2019).

### 4.6. Evolution History of M64

To explain the counterrotating gas in the outer disk of M64, it has been suggested that the progenitor spiral galaxy of M64 underwent a merger with a counterrotating gas-rich galaxy (Braun et al. 1992, 1994; Rubin 1994; Walterbos et al. 1994; Rix et al. 1995). Based on the result that only the outer gas disk...
is counterrotating while the outer stellar disk is corotating with the inner gas disk and stellar disk, they prefer mergers with a low-mass gaseous system.

Alternatively, they also suggested a continuous accretion of gas with an opposite sense of angular momentum. Several studies also showed that a majority of isolated S0 galaxies host extended counterrotating gas disks originated from external gas (Davis et al. 2011; Katkov et al. 2014, 2015). Especially, Katkov et al. (2014) mentioned that possible sources of external gas accretion are systems of dwarf gas-rich satellites or cosmological cold-gas filaments (Kereš et al. 2005; Dekel & Birnboim 2006).

Recently, Watkins et al. (2016) supported a merger scenario again to explain the presence of young stars in the inner disk, a red and featureless outer disk, and counterrotating gas in the outer disk of M64. The recent star formation is limited only to the inner disk, while the outer disk is quietly evolving. Thus, Watkins et al. (2016) pointed out that the merger played two opposite roles: it induced star formation in the inner region, while it removed gas and quenched star formation in the outer disk. They also suggested that M64 may be at the ending phase of a spiral galaxy being transformed to an S0 galaxy by merger-induced quenching. Indeed, the color of M64 is as red as S0a galaxies (Roberts & Haynes 1994) and Type III antitruncations are more frequently seen in S0 galaxies (Bolffaff et al. 2014).

More recently, Brunker et al. (2019) suggested another scenario that M64 had experienced a flyby interaction with a gas-rich galaxy rather than a merger. They suggested that a gas-rich progenitor of Coma P had a high speed flyby interaction with M64 approximately 1 Gyr ago, and some of the gas stripped from Coma P resulted in the counterrotating gas ring in the outer disk of M64. They also pointed out that young stars in Coma P seen in the CMD might have formed during the interaction of Coma P with M64.

From all the previous results, we support the scenario suggested by Brunker et al. (2019). The presence of old RGB stars in both M64 (in this study) and Coma P (Brunker et al. 2019) implies that both galaxies were formed more than 10 Gyr ago. The presence of young stars in Coma P and the central region of M64 strongly indicates a recent interaction between the two galaxies. The counterrotating gas ring with clumpy structure in M64 must have an external origin: either via accretion or flyby interaction of dwarf gas-rich satellites, or cosmological cold-gas filaments. Coma P is a strong candidate for providing the counterrotating gas to M64 through flyby interaction about 1 Gyr ago.

5. Summary and Conclusion

We presented deep F606W/F814W photometry of resolved stars in a field located in the outer disk of M64. We used it to explore the nature of stellar populations in the outer disk and find a clue to reveal the origin of the Type III component. Primary results are summarized as follows:

1. We discovered a new globular cluster, M64-GC1. The CMD of this cluster is well matched with 12 Gyr isochrones for low metallicity [Fe/H] = −1.5 ± 0.2, showing that it is a halo population.

2. CMDs of the resolved stars in the ACS field show two distinguishable stellar populations: metal-poor RGB stars and metal-rich RGB stars. In the CMDs, the metal-poor RGB is very similar to the RGB of the new halo globular cluster (M64-GC1), showing that the metal-poor RGB stars belong to the halo.

3. The radial number-density profile of the metal-rich RGB is described by an exponential disk law, while that of the metal-poor RGB is fit well be a de Vaucouleurs’s law. This shows that the metal-rich RGB represents the disk population with high metallicity, while the metal-poor RGB denotes the halo population with low metallicity.

From these results, we conclude that the origin of the Type III break in M64 is a halo rather than a disk or a bulge.

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Facility: HST(ACS).

Software: DrizzlePac (Gonzaga et al. 2012), DOLPHOT (Dolphin 2000), IRAF/ELLIPSE (Jedrzejewski 1987), GALFIT (Peng et al. 2010).

ORCID iDs

Jisu Kang @ https://orcid.org/0000-0003-3734-1995
Yoo Jung Kim @ https://orcid.org/0000-0003-1392-0845
Myung Gyooon Lee @ https://orcid.org/0000-0003-2713-6744
In Sung Jang @ https://orcid.org/0000-0002-2502-0070

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