A New Polar Ring Galaxy Discovered in the COSMOS Field

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Abstract

In order to understand the formation and evolution of galaxies fully, it is important to study their three-dimensional gravitational potential for a large sample of galaxies. Since polar-ring galaxies (PRGs) provide useful laboratories for this investigation, we have started our detailed study of a sample of known PRGs by using the data set obtained by the Hyper Suprime-Cam Subaru Strategic Program (HSC-SSP). During the course of this study, we have discovered a new PRG, identified as SDSS J095351.58+012036.1. Its photometric redshift is estimated as \( z \sim 0.2 \). The polar ring structure in this PRG appears to be almost perpendicular to the disk of its host galaxy without any disturbed features. Therefore, this PRG will provide us with useful information on the formation of such an undisturbed polar structure. We discuss its photometric properties in detail.

Unified Astronomy Thesaurus concepts: Galaxy colors (586); Galaxy photometry (611); Galaxy structure (622)

1. Introduction

Polar ring galaxies (PRGs) are galaxies with a polar structure (either a ring or a disk of gas, dust, and stars) rotating in a plane almost perpendicular to the major axis of its host galaxy. The archetypical PRG is NGC 2685 (or Arp 336). Sandage (1961) gives the following note on this galaxy; “There are two axes of symmetry for the projected image; most galaxies have only one.” Its host galaxy is an S0 galaxy, with the polar structure rotating through the minor axis of the host galaxy (Schechter & Gunn 1978). From a theoretical point of view, it is considered that the stable maintenance of the polar structure is due to the precessional motion of the polar structure (Steiman-Cameron & Durisen 1982).

So far, more than 400 candidates of PRGs have been discovered to date (e.g., Whitmore et al. 1990; Moiseev et al. 2011). However, among them, only dozens have been confirmed as real PRGs by spectroscopic observations (e.g., Egorov & Moiseev 2019). Since most galaxies reside in large-scale structures, interactions or mergers among galaxies are not rare events for them. In order to understand the dynamical and morphological evolution of galaxies, it is important to study how such interactions or mergers affect the evolution of galaxies by using large unbiased samples of PRGs. Indeed, observational properties of PRGs allow us to investigate a wide range of issues related to their galaxy formation and evolution (e.g., the baryonic matter accretion (e.g., Egorov & Moiseev 2019; Smirnov & Reshetnikov 2020), the rate of galaxy interactions or mergers (e.g., Reshetnikov et al. 2011; Reshetnikov 2019), and the 3D distribution of mass in the dark halo (e.g., Khoperskov et al. 2014; Zasov et al. 2017). In typical PRGs, their host galaxies are mostly early-type galaxies (E/S0), while their polar structures are generally young, blue, and gas rich (Reshetnikov & Mosenkov 2019). In addition, the observed polar structures show a wide variety in their morphology; e.g., a narrow ring or a wide annulus (Whitmore 1991), a spindle-, a Saturn-, or a worm-like structure (Faundez-Abans & de Oliveira-Abans 1998), inner polar structure (Moiseev 2012).

As for the formation of PRGs, the following three mechanisms have been theoretically proposed; galaxy mergers (e.g., Bekki 1997, 1998; Bournaud & Combes 2003), accretion of matter from an approaching galaxy (e.g., Reshetnikov & Sotnikova 1997; Bournaud & Combes 2003), and cold accretion from filaments in intergalactic space (e.g., Macciò et al. 2006; Brook et al. 2008; Snaith et al. 2012). However, it is still uncertain which mechanism is important for the formation of PRGs.

In order to improve the understanding of the formation and evolution of PRGs, we have started our systematic search for PRG candidates using the data set obtained by the Hyper Suprime-Cam Subaru Strategic Program (HSC-SSP; Aihara et al. 2018). During the course of this search, we have discovered a new PRG candidate SDSS J095351.58+012036.1 (hereafter J0953). This galaxy is located at the edge of the Cosmic Evolution Survey (COSMOS; Scoville et al. 2007) field. This survey covers a 2-square-degree field. It is designed to probe the galaxy formation and evolution as functions of both cosmic time (redshift) and the local galaxy environment. It is noted that only one PRG candidate has been found in the COSMOS Field; SPRC 093 (Moiseev et al. 2011).
In this paper, we discuss the observational properties of our new PRG candidate J0953. Throughout this paper, we use the following cosmological parameters: $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$, and $\Omega_{\Lambda} = 0.7$. All magnitudes given in this paper are in the AB magnitude system.

2. SDSS J095351.58+012036.1

The new PRG candidate in our study, J0953, is found at the eastern edge of the COSMOS field in Wide-layer images from the second Public Data Release (PDR2; Aihara et al. 2019) of HSC-SSP. The HSC-SSP survey consists of the following three layers: Wide, Deep, and UltraDeep. The Wide layer covers about 300 deg$^2$ in all the five broad-band filters (grizy) to the nominal survey exposure (10 minutes in gr and 20 minutes in izy).

The HSC-SSP PDR2 data have already been processed with the data reduction pipeline hsc Pipe version 6 (Bosch et al. 2018; Aihara et al. 2019), including the following procedures; the point-spread function (PSF) modeling, object detection, and photometry.

In Figure 1(a), we show the g-, r-, and i-band composite image of J0953 taken by hsc Map tool$^5$ (Koike 2019) with SDSS TRUE COLOR mixer. Apparently, a polar structure or ring can be seen in an NE-SW direction almost perpendicular to the disk of the host galaxy.

J0953 is identified as a galaxy by the Sloan Digital Sky Survey (SDSS; York et al. 2000); SDSS J095351.58+012036.1. Its photometric properties are reported as follows; $u' = 21.49 \pm 0.25$ mag, $g' = 19.73 \pm 0.03$ mag, $r' = 18.83 \pm 0.02$ mag, $i' = 18.34 \pm 0.025$ mag, and $z' = 18.02 \pm 0.05$ mag. These data give a photometric redshift of 0.146 $\pm$ 0.036 (Beck et al. 2016). Note that there is no spectroscopic observation of J0953 and thus no spectroscopic redshift is available.

In Table 1 we present the photometric properties of J0953 taken from the HSC-SSP database by CAS search tool.$^6$ It is noted that the magnitudes given in this table are slightly brighter than the SDSS magnitudes given above. We consider that this slight difference is probably due to the deeper imaging of the HSC-SSP Wide layer. Using these photometric data, the HSC-SSP group estimates photometric redshifts of J0953 using the two codes. One is the DEmP code (Hsieh & Yee 2014), and the other is the MIZUKI code (Tanaka 2015). These two codes give $z = 0.19$ (DEmP) and $z = 0.20$ (MIZUKI), respectively. Since these are consistent within their errors, we adopt the photometric redshift of J0953, $z = 0.20$ in this paper. This gives the luminosity distance of J0953, 980 Mpc.

We note that there are neither companion galaxies nor satellite galaxies around J0953. In Figure 1, however, there appear two faint objects about 5$''$7 in both east and west of J0953. Based on their photometric properties, they are background galaxies with photometric redshifts of $z \sim 1.3$, respectively.

3. Results and Discussion

We discuss the possibility that J0953 is the PRG. To do so, we need to examine whether at least one of the two components that appear to be vertically intersecting the host galaxy or polar structure is the disk or the ring.

First, PSFs of the g, r, i, z, and y bands of J0953 are obtained by using the PSF picker.$^7$ Next, the FWHM values of these PSFs are obtained by using the IRAF$^8$ task IMEXAMINE.

\begin{table}[h]
\centering
\caption{Properties of J0953 from the HSC-SSP Database}
\begin{tabular}{l|l}
\hline
Property Name & Data \\
\hline
R.A. (J2000.0) & 09h53m51s59 \\
decl. (J2000.0) & +01d20'36.3 \\
g & 19.43 \\
r & 18.58 \\
i & 18.12 \\
z & 17.75 \\
y & 17.65 \\
Photometric redshift (MIZUKI) & 0.19$^{\pm}$0.05 \\
Photometric redshift (DEmP) & 0.20$^{\pm}$0.06 \\
Stellar mass (MIZUKI) & $3.85^{+3.10}_{-2.10} \times 10^{10}$ $M_\odot$ \\
Star formation rate (MIZUKI) & $2.66^{+7.77}_{-3.52} \ M_\odot$ yr$^{-1}$ \\
Interstellar absorption: $A_V$ (MIZUKI) & $0.65^{+0.22}_{-0.33}$ \\
\hline
\end{tabular}
\end{table}

Note. We note that the photometric errors in all the five bands are less than 0.01 mag.

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{image}
\caption{The gri composite image of J0953 taken from the hsc Map (Dataset: PDR2 WIDE, Mixer: SDSS TRUE COLOR). North is up and east is left. The white bar displayed in panel (b) corresponds to the angular size of 5$''$, or $\approx$24 kpc at $z = 0.2$ (see text). The solid and dashed lines in panel (b) show the half-light radii of the host galaxy and polar structure, respectively.}
\end{figure}

$^5$ hsc Map: \url{https://hsc-release.mtk.nao.ac.jp/hscMap-pdr2/app/}.

$^6$ CAS search: \url{https://hsc-release.mtk.nao.ac.jp/dataset/?}

$^7$ PSF picker: \url{https://hsc-release.mtk.nao.ac.jp/psf/pdr2/?}

$^8$ IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
The PSF of each band in arcsec is as follows; 0.75 (g), 0.85 (r), 0.63 (i), 0.78 (z), and 0.64 (y).

Since the PSF size is the largest in the r band, the other band images are convolved with Gaussian kernels to fit to the r-band one by using the IRAF task GAUSS. In the subsequent analyses, we use these smoothed images.

In order to investigate the structural properties of both the polar ring and its host galaxy, we have made the g-, r-, i- combined image of J0953 to improve the signal-to-noise ratio. Then, we have carried out the two-component fitting for both the polar ring and the host galaxy, each of which has a Sérsic component. In this analysis, we use the GaLight package (version 0.1.6: Ding et al. 2020; Ding et al. 2021).

The fitting results are summarized in Table 2. The obtained ellipses with the half-light radius are shown in Figure 1(b).

The Sérsic index for the host galaxy is 2.94, suggesting that the host galaxy has an elliptical galaxy-like structure rather than an exponential disk. However, Vika et al. (2015) reports that the average of the Sérsic index for the Sab-Sb galaxies is 2.9. Therefore, it is also possible that the host galaxy is a disk galaxy.

On the other hand, the polar structure has the flatter light profile than the exponential disk; its Sérsic index is 0.47, being much less than 1. This small Sérsic index is consistent with that the polar component has a ring-like structure. Further imaging observation with a higher spatial resolution is necessary to confirm if the polar structure is a ring or not.

Next, with the structure parameters fixed as those in Table 2, we have performed model decomposition by using GaLight in each of the g, r, i, z, and y images of J0953 to measure apparent magnitudes of each component. Table 3 lists the apparent magnitudes and the absolute magnitudes of the host galaxy and the polar structure.

The spectral energy distribution (SED) of the galaxy is a composite of the spectral emissions from all the stars contained therein. Therefore, we can estimate the stellar mass of both the host galaxy and the polar structure.

Here, we use the absolute magnitudes in i-band and the color g-i following the method outlined by Taylor et al. (2011), and obtain the stellar mass of the host galaxy and the polar structure are $26.18 \times 10^9 M_\odot$ and $4.23 \times 10^9 M_\odot$, respectively.

The characteristic absolute magnitude $M_\ast$ corresponding to the characteristic luminosity $L_\ast$ of the galaxies are suggested from Blanton et al. (2001) as follows; $u' = -18.34 \pm 0.08$ mag, $g' = -20.04 \pm 0.04$ mag, $r' = -20.83 \pm 0.03$ mag, $i' = -21.26 \pm 0.04$ mag, and $z' = -21.55 \pm 0.04$ mag; see Table 1 of Blanton et al. (2001) for details on the sample galaxies.

Using the color conversion formulae from the SDSS system to the HSC system from Komiyama et al. (2018), these $M_\ast$ are converted to $g = -20.12$ mag and $i = -21.31$ mag. The $g-i$ band absolute magnitudes of the J0953 host galaxy are $-20.30$ mag and $-21.34$ mag, respectively. Therefore, the host galaxy of J0953 is possibly brighter and heavier than the galaxies of the characteristic luminosity $L_\ast$ corresponding to the characteristic absolute magnitude $M_\ast$.

Figure 2 is the color–color diagrams to estimate one of the information, and the colors of the host galaxy and the polar structure of this galaxy at $z \sim 0.20$ are plotted.

Figure 2 is the color–color $(r-i$ versus $g-r$) diagram of the host galaxy and the polar structure compared with that of each Hubble type of typical galaxies at $z \sim 0.2$ (Fukugita et al. 1995). The colors of the host galaxy suggest a Sab-Sb galaxy while host galaxies of typical PRGs are mostly early-type galaxies (E/S0) (Reshetnikov & Mosenkov 2019). The polar structure is similar in colors to Scd galaxies. This is consistent with that the polar structure is blue and probably younger than the host galaxy. In order to confirm if this galaxy is truly a PRG, it is necessary to make spectroscopic observations, to investigate the kinematical properties of both the host galaxy and the polar structure.

| Table 2 | Structural Parameters$^a$
| Parameter Name | Host Galaxy | Polar Structure |
|------------|-------------|-----------------|
| effective radius (°) | 0.89 | 2.12 ± 0.01 |
| Sérsic index | 2.94 ± 0.02 | 0.47 |
| position angle (°) | 102.2 ± 0.5 | 31.4 ± 0.1 |
| axis ratio$^b$ | 0.71 | 0.28 |

Notes. No error means that the error is less than 0.01 in each case.

$^a$ The structural parameters were estimated on the combined image of the g, r, and i images by GaLight.

$^b$ The axis ratio is the semiminor to semimajor axis ratio.

| Table 3 | Estimated Magnitudes
|----------|-----------------|-----------------|-----------------|-----------------|-----------------|
| m$^g$ | 20.07 | 19.14 | 18.67 | 18.29 | 18.17 |
| m$^r$ | 21.02 | 20.41 | 20.00 | 20.01 | 19.76 |
| m$_{HG}^g$ | -20.30 | -20.92 | -21.34 | -21.73 | -21.82 |
| m$_{PR}^g$ | -19.09 | -19.52 | -19.85 | -19.88 | -20.22 |

Note. Note that $m$ and $M$ are the apparent and absolute magnitudes, respectively. HG and PR are the host galaxy and the polar structure, respectively. We note that the photometric errors in all the five bands are less than 0.01 mag. The absolute magnitudes are corrected for the Galactic extinction using the values listed in the HSC-SSP PDR2 data, which are estimated from the dust maps given in Schlegel et al. (1998); see also Aihara et al. (2019). The $k$-correction is applied for all the absolute magnitudes (Chilingarian et al. 2010).

9 GaLight is a Python-based open-source package for 2D model fitting of galaxy images in cooperation with lenstronomy (Birrer & Amara 2018; Birrer et al. 2021).
Figure 2. The $r-i$ vs. $g-r$ diagram. The filled circles show the colors for 5 morphology types (E, S0, Sab, Sbc, and Scd) of galaxies in Fukugita et al. (1995). The solid line shows the best linear fit to the colors of 5 morphology types. The open circles of HG and PR show the colors of the host galaxy and the polar structure of J0953. The star mark with HSC shows the colors taken from Table 1 of J0953. All of the above colors are at $z \sim 0.2$ and corrected for the Galactic extinction.

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