Mon. Not. R. Astron. Soc. **000**, 1–8 (2004) Printed 19 January 2014 (MN LATEX style file v2.2)

Are Passive Spiral Galaxies Truly "Passive" and "Spiral"? : Near-Infrared Perspective

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19 January 2014

ABSTRACT

Passive spiral galaxies — unusual galaxies with spiral morphology without any sign of on-going star formation — have recently been discovered to exist preferentially in cluster infalling regions (at about the virial radius, or at a local galaxy density of ~ 1 Mpc^{-2}). The discovery directly connects the passive spiral galaxies to the cluster galaxy evolution studies such as the Butcher-Oemler effect or the morphology-density relation, i.e., passive spiral galaxies are likely to be transition objects between high-z blue, spiral galaxies and low-z red, cluster early-type galaxies. Thus, detailed study of passive spiral galaxies potentially could bring a new insight on the underlying physical mechanisms governing cluster galaxy evolution. However, in previous work, passive spiral galaxies are selected from the low resolution optical images with ~ 1.5 arcsec of seeing. Therefore, passive spirals could be a mis-identification of S0 galaxies; or dusty-starburst galaxies which are not passive at all.

To answer these questions, we performed a deep, high-resolution, near-infrared imaging of 32 passive spiral galaxies. Our high resolution K band images show clear spiral arm structures. Thus, passive spirals are not S0s. Optical-infrared colour does not show any signs of dusty-starburst at all. Therefore, it is likely that they are truly "passive" and "spiral" galaxies in the midst of cluster galaxy evolution.

Key words: galaxies: clusters: general

1 INTRODUCTION

It is a remarkable feature that galaxy properties correlate with the environment where that galaxy exists. It has been well established that in the dense regions such as galaxy cluster cores, E/S0 galaxies are dominant, and that in the rarefied field regions, spiral galaxies are more numerous (Dressler 1980; Postman & Geller 1984; Whitmore et al. 1993; Whitmore 1995; Dressler et al. 1997; Hashimoto & Oemler 1999; Fasano et al. 2000; Tran et al. 2001; Domínguez et al. 2001, 2002; Helsdon & Ponman 2003; Treu et al. 2003; Goto et al. 2003a). This is the so-called morphology-density relation. As wide area CCD based surveys and large & uniform galaxy cluster catalogs become available (Postman et al. 1996; Annis et al. 1999; Kim et al. 2002; Goto et al. 2002a,b; Postman et al. 2002; Gal et al. 2003; Popesso et al. 2004), recent studies on the morphology-density relation started to reveal the environment where galaxy morphology start to change (Hogg et al. 2003; Blanton et al. 2003a;Tanaka et al. 2004). Goto et al. (2003a) revealed that the morphology-density relation has two different breaks at local galaxy densities of 1 Mpc^{-2} and 0.3 Mpc^{-2}, possibly indicating the existence of two different physical mechanisms.

Not only morphology but the star formation rate (SFR) of galaxies correlates with environments. It has been known for a long time that galaxy SFR is lower in the cluster core regions, resulting in numerous red galaxies in cluster cores (e.g., Couch & Sharples 1987;Couch et al. 1994,1998; Dressler et al. 1994; Abraham et al. 1996; Pimbblet et al. 2002). Recently it has become possible to specify the environment where SFR suddenly start to change (e.g. Kodama et al. 2001; Tanaka et al. 2004). Interestingly, this environment where SFR changes coincides with the environment where galaxy morphology changes (Goto et al. 2004; Tanaka et al. 2004). Cluster galaxies change their SFR in the same environment where they change their morphology.

It has also been known that cluster galaxies evolve. Butcher & Oemler (1978,1984) found that fractions of blue galaxies in clusters increase with increasing redshift, i.e., cluster galaxies evolve from blue to red. This Butcher-Oemler effect was later confirmed by many authors (Rakos, Schombert 1995; Couch et al. 1994,1998; Margoniner, de Carvalho 2000; Margoniner et al. 2001; Ellingson et al. 2001; Kodama & Bower 2001; Goto et al. 2003b, but also see Andreon et al. 1999,2003). High redshift clusters ($z \sim 0.9$) are also known to have larger fractions of star-forming galaxies than

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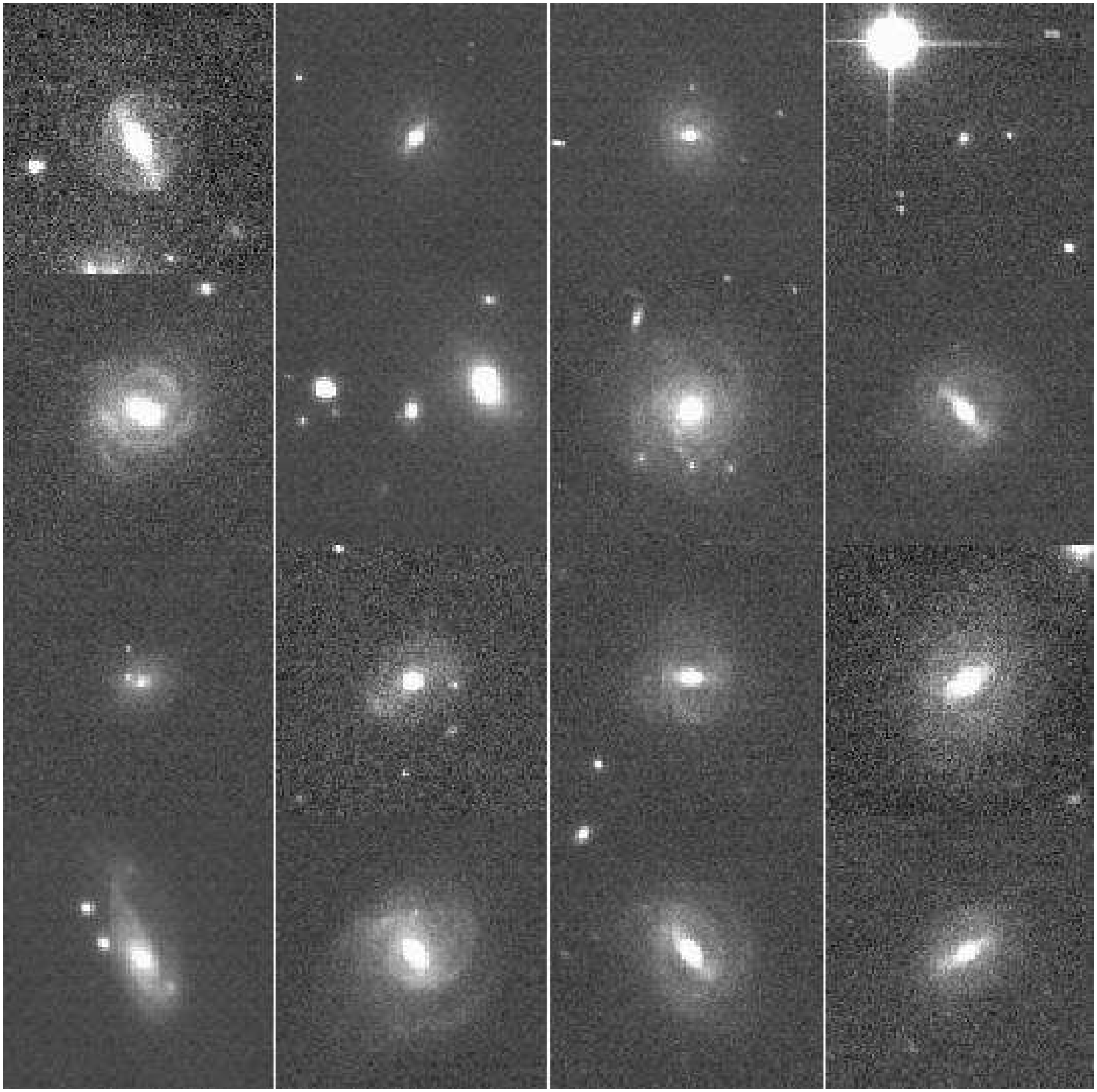

Figure 2. The UKIRT K band images of the observed passive spiral galaxies. Each image is 35×35 arcsec. The figures are listed in the same order as in Table 1 from the top left corner.

local clusters (Postman, Lubin, & Oke 1998; Postman, Lubin, & Oke 2001). Morphologically, it is found that fractions of S0 galaxies are higher in high redshift clusters (Dressler et al. 1997; van Dokkum et al. 1998; Fasano et al. 2000; Jones, Smail, & Couch 2000; Fabricant et al. 2000; also see Andreon et al. 1998). This claim was confirmed later by Goto et al. (2003b,2004) using the statistical number of 516 clusters found in the Sloan Digital Sky Survey (SDSS; Goto et al. 2002a,b).

From these numerous pieces of observational evidence, we know that some physical mechanism is changing the morphology and SFR of cluster galaxies as a function of the redshift. However to date, it has been difficult to specify what physical mechanisms determine morphology and SFR of galaxies. It has been simply difficult to trace the complicated process of galaxy evolution with several Giga years of timescale, using the observation of only a single epoch.

However, recently, a population of galaxies which are likely to shed some light on the subject has been actively debated. The galaxies are called passive spiral galaxies (Couch et al. 1998; Dressler et al. 1999; Poggianti et al. 1999). Despite their spiral ap-

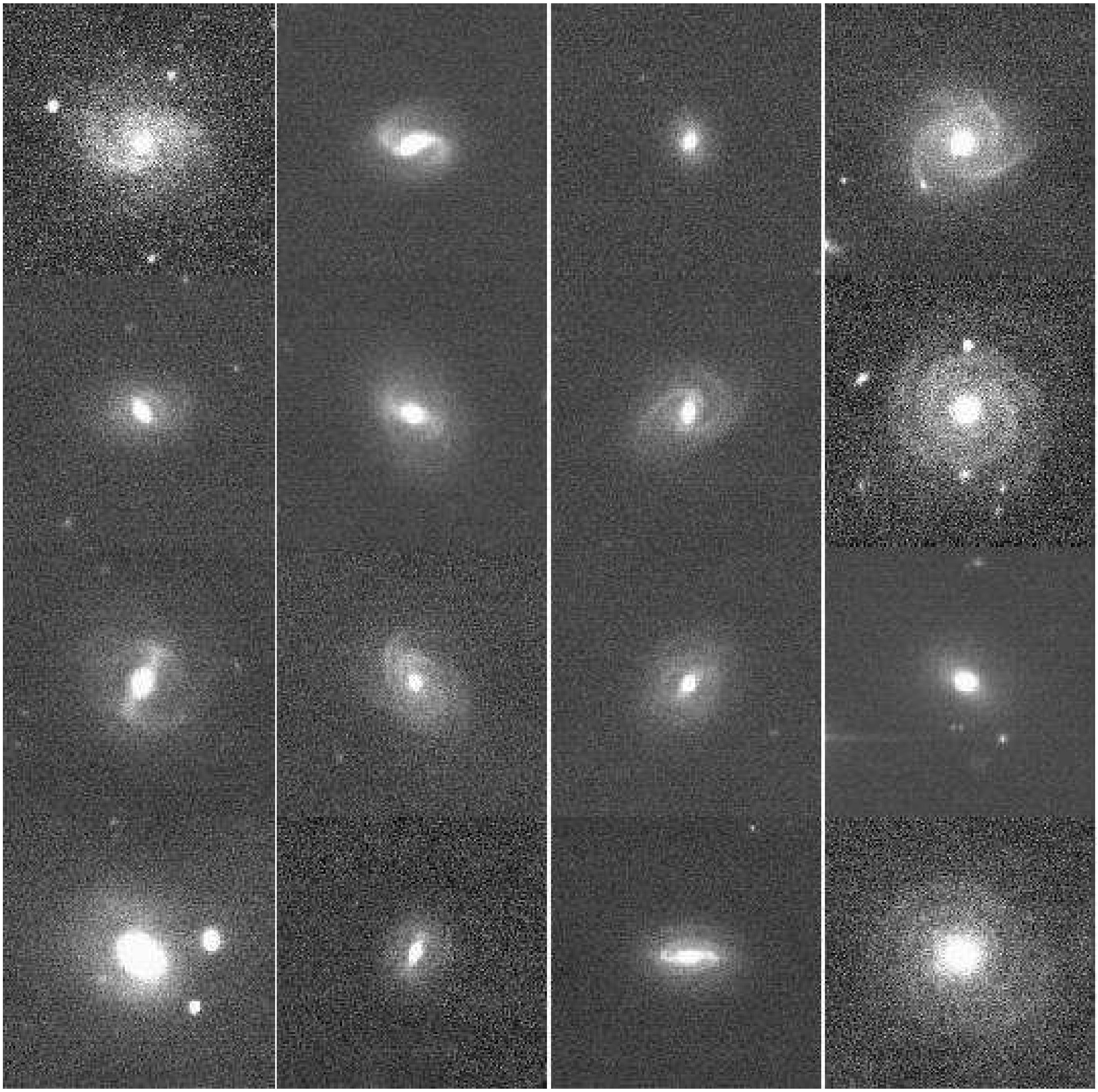

Figure 2 – *continued*

pearances, passive spirals do not have any emission lines indicative of on-going star formation. Passive spirals have been known to exist in many cluster studies (van den Bergh 1976; Wilkerson 1980; Bothun & Sullivan 1980; Phillipps 1988; Cayatte et al. 1994; Couch et al. 1998; Poggianti et al. 1999; Bravo-Alfaro et al. 2001; Elmegreen et al. 2002). However, their abundance in the field region was not studied well. And thus, their connection to the cluster regions has not been clear until the recent discovery by Goto et al. (2003c), which claims that passive spiral galaxies exist preferentially in perimeter regions of galaxy clusters at around the virial radius of or local galaxy density of ~ 1 Mpc^{-2}. Suggesting that passive spiral galaxies are created by some cluster related physical mechanism, this discovery will bring significant implications on the underlying physical mechanism. Since passive spirals are expected to evolve into red, early type cluster galaxies in a few Gyr, passive spirals are likely to be intermediate transition objects between high-z blue, spirals and low-z red, early type cluster galaxies. And thus, by studying passive spiral galaxies in detail, we may be able to specify the physical mechanism responsible for the cluster galaxy evolution.

However, since the result of Goto et al. (2003c) was based on the SDSS and the Two Micron All Sky Survey (2MASS; Jarrett et

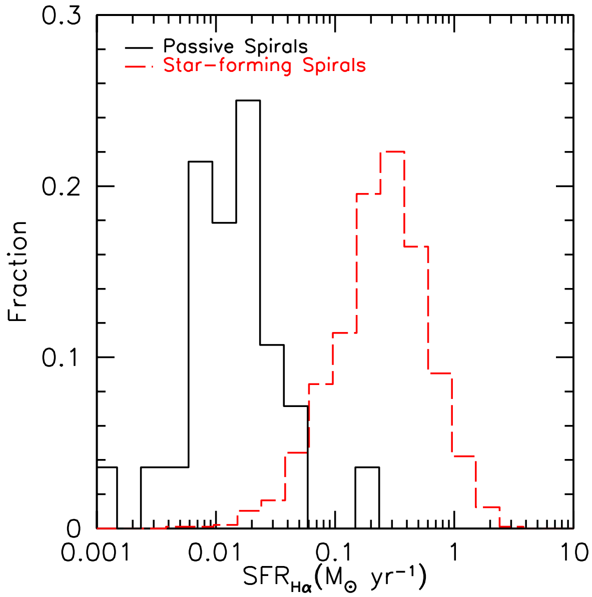

Figure 1. The distributions of SFR estimated from the Hα luminosity. The solid line and the dashed line are for the passive spiral galaxies and the star-forming galaxies, respectively. Note that these SFRs of passive spiral galaxies (the solid line) should be considered as upper limits since the Hα line is not detected in these passive spiral galaxies and the continuum around Hα wavelength is used to estimate the presented SFR.

al. 2000) data, which have relatively poor image resolution (~ 1.5 arcsec of seeing) and large photometric error, there have been two remaining important uncertainties before interpreting passive spirals as transition objects:
(i) Are passive spirals not S0s?;
(ii) Are passive spirals not dusty starburst galaxies?
If Goto et al. (2003c) mis-identified some S0 galaxies as passive spirals due to the poor seeing condition of the SDSS (~ 1.5 arcsec), their discovery is less interesting since S0 galaxies are more common and very well studied in the literature. Also, if the emission lines of passive spirals are just suppressed by the heavy obscuration by dust in optical wavelength, passive spirals might not be passive at all.

In order to answer these two questions, we performed a deep K band imaging of passive spiral galaxies. Deeper imaging will reveal detailed morphology of passive spirals. In addition, near-infrared light is less affected by the dust extinction, and thus allows us to distinguish dusty starburst galaxies from passive spirals.

This paper is organized as follows: In Section 2, we describe the deep K band observations we performed; In Section 3, we present the results; In Section 4, we discuss the physical implications of our results; In Section 5, we summarize our work and findings. The cosmological parameters adopted throughout this paper are H_0=75 km s^{-1} Mpc^{-1}, and (Ω_m,Ω_Λ,Ω_k)=(0.3,0.7,0.0).

2 UKIRT OBSERVATION

We have selected our target galaxies from 73 passive spiral galaxies presented in Goto et al. (2003c). All 73 passive spiral galaxies do not have any emission in [OII] nor Hα ($< 1\sigma$ in equivalent width) and have disc-like morphology. This sample is selected from a volume limited sample of galaxies ($0.05 < z < 0.1$, $M_r < -20.5$) based on the Sloan Digital Sky Survey data (Abazajian et al. 2003), and therefore is free from Malmquist type of bias. Fig. 1 shows the distribution of star formation rate (SFR) for these 73 passive spiral galaxies computed from the luminosity in Hα (the solid line). The SFR is calculated using a conversion formula given in Kennicutt (1998), assuming constant extinction of 1 magnitude at the wavelength of Hα. We caution readers that these SFRs of passive spiral galaxies should be considered as upper limits since the Hα line is not detected in these passive spiral galaxies and the continuum around Hα wavelength is used to estimate the SFR in Fig. 1. As a comparison sample, we have selected star-forming spiral galaxies as galaxies with both detected [OII] and Hα emission lines (with $> 1\sigma$ significance) and with the concentration index consistent to be a spiral ($Cin_r > 0.5$). Here, Cin_r is defined as the ratio of Petrosian 50% flux radius to Petrosian 90% flux radius in r (Shimasaku et al. 2001). The distribution of SFR in the star-forming spiral galaxies is shown with the dashed line in Fig. 1. Compared with the star-forming spiral galaxies (the dashed line), our target passive spiral galaxies (the solid line) have lower SFR by about an order (or more). The difference again demonstrate that our target passive spiral galaxies indeed have much lower SFR than normal spiral galaxies in the field region.

Among 73 passive spiral galaxies, all 32 passive spiral galaxies accessible during the run on 2003 September 10-11 were observed on the 3.8m United Kingdom Infrared Telescope (UKIRT) in the K band (2.2 μm) using the UKIRT Fast Track Imager (UFTI). UFTI is a 1-2.5 μm InSb imager with 1024 $\times$ 1024 pixel. Each pixel subtends 0.091 arcsec on the sky. UFTI's field of view is $\sim$ 90 arcsec. Data were taken in periods of good atmospheric transparency and with the excellent seeing of $\sim$0.5 arcsec. For each galaxy, we used two sets of 3$\times$3 grid of dithered position exposures of 60 sec each. The integration time is 18 mins for each galaxy. Calibration was obtained by observing a selection of UKIRT faint standards (Hawarden et al. 2001) on each night. The data were analyzed with the ORAC-DR data reduction pipeline which automates the dark subtraction, flat-fielding, re-sampling and de-spiking processes. The photometry was performed using IRAF (v2.12.1) `phot` routines within 2$\times$ Petrosian radius measured in the SDSS r band image (Stoughton et al. 2002).

In addition to the 32 passive spiral galaxies, we have observed 12 early-type galaxies as a control sample. These early-type galaxies were selected from the same volume limited sample ($0.05 < z < 0.1$, $M_r < -20.5$) as galaxies with $Cin_r < 0.4$, and thus mainly consist of elliptical and S0 galaxies. We compare this control sample with passive spiral galaxies in order to test truly "passive" and "spiral" nature of the galaxies.

The purpose in using K band is two-folded. First, the K band is relatively free from dust extinction. Therefore, we can test dust extinction in passive spirals using $r - K$ colour. Also, since the K band traces the old stellar population, i.e., the dominant mass distribution in galaxies, it is suitable to study galaxy morphology.

3 RESULTS

3.1 K-band Galaxy Morphology

First, we present K band morphology of passive spirals to make sure that they are not S0 galaxies, which are more common and known to have passive nature. In Fig. 2, we show K band images of 32 passive spiral galaxies taken with the UKIRT. The deep and high resolution imaging capability of UKIRT can probe the discs and

Table 1. List of observed targets.

Name	R.A.	Dec.	Redshift	K	K_{err}	C_{in}(K)	
SDSSJ004339.22+151025.6	0:43:39.22	15:10:25.64	0.081	13.789	0.015	0.26	
SDSSJ010647.55+140048.1	1:06:47.55	14:00:48.13	0.089	13.532	0.005	0.39	
SDSSJ010955.90+154757.4	1:09:55.90	15:47:57.40	0.062	13.344	0.007	0.47	
SDSSJ012409.19-002555.9	1:24:09.19	-0:25:55.97	0.080	16.032	0.025	0.14	†
SDSSJ012528.30+004411.7	1:25:28.30	0:44:11.75	0.089	12.513	0.006	0.47	
SDSSJ015855.15-095143.2	1:58:55.15	-9:51:43.25	0.082	14.316	0.005	0.93	‡
SDSSJ021534.36-090537.0	2:15:34.36	-9:05:37.06	0.069	12.219	0.004	0.49	
SDSSJ024732.02-065137.4	2:47:32.02	-6:51:37.48	0.071	13.044	0.008	0.49	
SDSSJ033322.66-000907.5	3:33:22.66	-0:09:07.51	0.085	14.178	0.019	0.52	
SDSSJ074452.51+373852.7	7:44:52.51	37:38:52.73	0.074	13.932	0.008	0.49	
SDSSJ143320.16+003952.7	14:33:20.16	0:39:52.71	0.078	12.890	0.010	0.53	
SDSSJ151033.69+021434.8	15:10:33.69	2:14:34.81	0.074	12.821	0.013	0.30	
SDSSJ151747.79+030052.1	15:17:47.79	3:00:52.15	0.082	11.606	0.004	0.46	
SDSSJ152621.67+035002.4	15:26:21.67	3:50:02.46	0.083	12.017	0.006	0.46	
SDSSJ161125.21+524526.8	16:11:25.21	52:45:26.87	0.063	12.524	0.007	0.49	
SDSSJ161655.51+521449.2	16:16:55.51	52:14:49.25	0.089	13.559	0.012	0.53	
SDSSJ163340.30+475018.4	16:33:40.30	47:50:18.44	0.061	13.496	0.010	0.57	
SDSSJ174218.49+551537.5	17:42:18.49	55:15:37.53	0.062	12.973	0.010	0.53	
SDSSJ222206.46-011002.7	22:22:06.46	-1:10:02.77	0.100	14.402	0.016	0.48	
SDSSJ223239.13-082323.1	22:32:39.13	-8:23:23.13	0.080	12.863	0.008	0.54	
SDSSJ223558.39-002313.8	22:35:58.39	-0:23:13.84	0.080	13.660	0.013	0.48	
SDSSJ224000.16-004945.1	22:40:00.16	-0:49:45.15	0.053	12.683	0.009	0.51	
SDSSJ224435.97-081615.5	22:44:35.97	-8:16:15.58	0.082	13.047	0.014	0.50	
SDSSJ224747.17+125125.9	22:47:47.17	12:51:25.96	0.092	12.990	0.009	0.59	
SDSSJ231642.88+153954.5	23:16:42.88	15:39:54.58	0.091	12.882	0.010	0.52	
SDSSJ232259.44+145915.4	23:22:59.44	14:59:15.46	0.095	13.570	0.012	0.56	
SDSSJ233354.88-002449.3	23:33:54.88	-0:24:49.39	0.088	13.214	0.008	0.54	
SDSSJ234036.90+142943.4	23:40:36.90	14:29:43.44	0.067	12.877	0.003	0.41	
SDSSJ234206.04+150129.0	23:42:06.04	15:01:29.05	0.066	12.056	0.006	0.44	
SDSSJ234523.98+010552.0	23:45:23.98	1:05:52.00	0.059	13.787	0.028	0.53	
SDSSJ235307.15+150355.3	23:53:07.15	15:03:55.38	0.079	13.174	0.013	0.46	
SDSSJ235741.11+004135.7	23:57:41.11	0:41:35.74	0.061	13.337	0.027	0.48	

† – A bright star in the same field.
‡ – A possible overlap with a bright nearby galaxy.

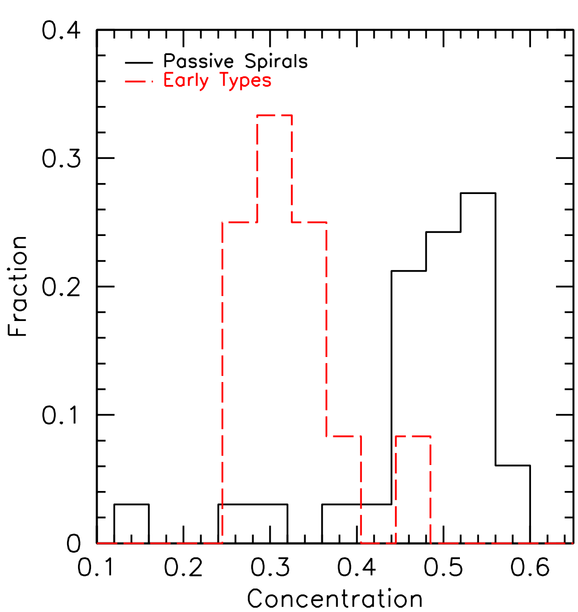

Figure 3. Distribution of concentration parameter, Cin_K, measured as a ratio of Petrosian 50 to 90% flux radius in K band.

spiral arm structures in the passive spiral galaxies. Although there are two cases where disc structures are not clear due to the presence of a nearby bright object (SDSSJ012409.19-002555.97 and SDSSJ015855.17-105143.25), the rest of the passive spiral galaxies have discs and spiral arm structures without contamination from more common S0 galaxies.

Qualitatively, we measured the concentration of passive spiral galaxies as a ratio of Petrosian 50% flux radius to 90% flux radius using the flux measured in the K band. Note that this concentration parameter, Cin_K, is an inverse of the commonly used concentration parameter, and thus, later-type galaxies have $larger$ values of Cin_K. Since our K band images are much deeper with twice as high resolution as the SDSS images, Cin_K provides us with a better description of galaxy morphology than the concentration parameter used in Goto et al. (2003). Since the seeing size was almost constant during the two days of observation (~ 0.5 arcsec) and our galaxies are at a similar redshift ($z \sim 0.08$), we did not correct for the seeing. In Fig. 3, we show the distribution of Cin_K for both the passive spirals (the solid line) and the control sample (the dashed line). Reassuringly, passive spiral galaxies and the control sample of early type galaxies have a very different Cin_K distribution, with passive spirals having much higher values of Cin_K. A Kolomogorov-Smirnov test shows that these two distributions are different with more than 99.99% significance. This difference in

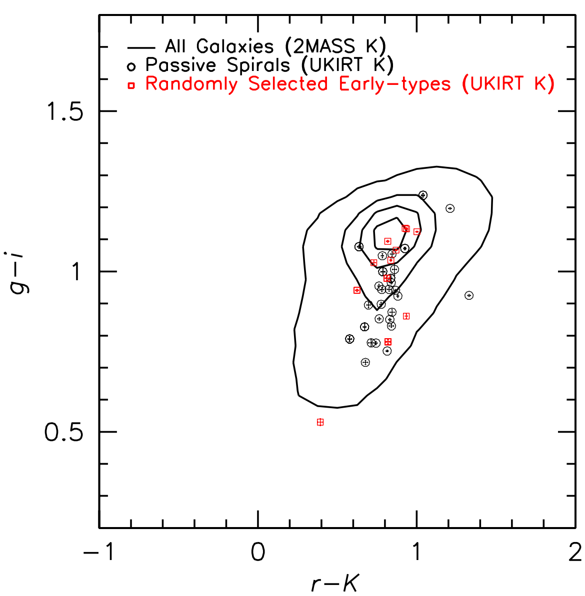

Figure 4. Restframe $g - i$ vs. $r - K$ two-colour diagram. The circles are for passive spirals. The squares are for the early-type galaxies in the control sample. The contours represent all galaxies in the volume limited sample with 2MASS K magnitude. The error bars are shown inside the circles and squares.

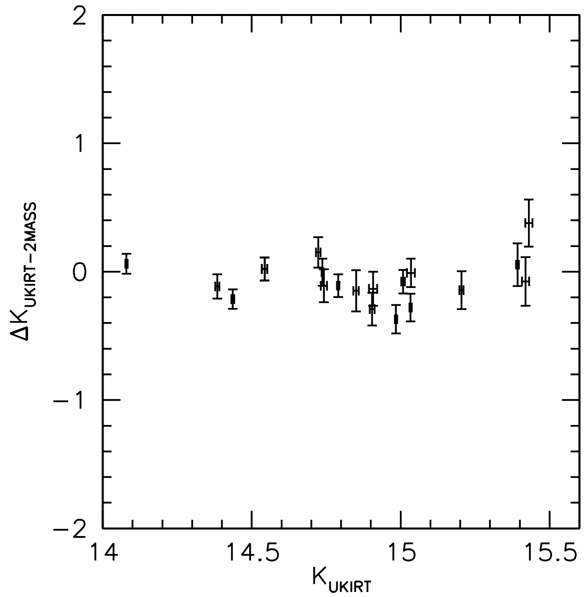

Figure 5. Offsets between UKIRT K magnitude and 2MASS K magnitude are shown for 22 galaxies commonly observed with both of the two telescopes. The mean deviation and rms is 0.05 and 0.17, respectively. Note that K is in AB system in this figure.

the Cin_K distribution assures that our passive spiral galaxies are indeed different galaxy population than well-studied S0 galaxies.

3.2 Optical-Infrared Colour

Next, we present optical-infrared ($r - K$) colour distribution of passive spiral galaxies in order to check whether they are dusty starburst galaxies or truly passive galaxies. Since K band is less affected by the dust extinction than r band, dusty starburst galaxies are known to have redder colours in $r - K$ by ~ 1 mag (Smail et al. 1999) . Fig. 4 plots $g - i$ colour against $r - K$ colour. Optical photometries ($g, r,$ and i) are from the SDSS and k-corrected to the restframe using the routine given in Blanton et al. (2003b; v1_11). The black circles are for passive spiral galaxies observed with UKIRT. The squares are for early-type galaxies in the control sample. For a reference, we plot the distribution of all galaxies in the volume limited sample with K magnitudes measured with the Two Micron All Sky Survey (2MASS; Jarrett et al. 2000) as the contour. When comparing 2MASS K magnitude with the UKIRT K magnitudes, we found a slight shift between these two magnitudes as shown in Fig. 5. We have calibrated this offset using 22 galaxies commonly observed with both 2MASS and UKIRT to match UKIRT K mag to 2MASS K mag. K band magnitudes are K-corrected using Mannucci et al. (2001). The error bars are plotted as horizontal and perpendicular bars. Compared with the error with 2MASS K ($\Delta K \sim 0.1$), the UKIRT observation reduced the error in K magnitude significantly ($\Delta K < 0.03$; c.f. Fig. 13 of Goto et al. 2003c). Interestingly, compared with all galaxies (the contour), passive spiral galaxies (circles) are not redder at all in $r - K$ colour. Indeed, $r - K$ colours of passive spiral galaxies are indistinguishable from early-type galaxies (squares). These results support truly passive nature of these galaxies since dusty starburst galaxies should have $r - K$ colour by 1 magnitude redder than normal galaxies (i.e., $r - K \sim 1.8$; See Smail et al. 1999).

4 DISCUSSION

In Section 3, we have answered the two remaining questions on passive spiral galaxies using the deep K band imaging with UKIRT; (i) passive spiral galaxies indeed have discs & spiral arm structures, and therefore they are a different population of galaxies from S0 galaxies; (ii) optical-infrared ($r - K$) colour does not show any signs of dusty starburst galaxies. Therefore, they must be truly passive galaxies. In this section, we discuss physical implications of our results. Since our UKIRT observation has secured that passive spiral galaxies are truly spiral galaxies with no star formation, we now have to take it more seriously that these passive spiral galaxies exist in the cluster perimeter regions (Goto et al. 2003c).

It has been long discussed whether the properties of cluster galaxies are by their 'nature' or 'nurtured' later. According to the standard hierarchical clustering model, galaxies in high density regions of the Universe such as galaxy clusters have collapsed earlier, and thus more evolved than galaxies in the low density field regions. In addition to this, galaxies in dense regions have been subject to additional physical mechanisms specific to the dense regions. Therefore, it is important to understand whether properties of cluster galaxies were established early in the universe when the galaxy assembled (nature), or they are later formed by the physical mechanisms specific to the dense regions (nurture). Goto et al. (2003c) have found that passive spiral galaxies preferentially exist in cluster perimeter regions. If passive spiral galaxies do not exist in the low density field regions, the result may favor the 'nurture' scenario where only cluster specific physical mechanisms can create passive spiral galaxies.

Various physical mechanisms have been proposed to explain the cluster galaxy evolution. Possible mechanisms include ram-pressure stripping of gas (Gunn & Gott 1972; Farouki & Shapiro 1980; Kent 1981; Fujita & Nagashima 1999; Abadi, Moore & Bower 1999; Quilis, Moore & Bower 2000; Fujita & Goto 2004); galaxy harassment via high speed impulsive encounters (Moore et al. 1996, 1999; Fujita 1998); cluster tidal forces (Byrd & Valtonen 1990; Valluri 1993; Fujita 1998; Gnedin 2003a,b) which distort galaxies as they come close to the centre; interaction/merging of galaxies (Icke 1985; Lavery & Henry 1988; Mamon 1992; Makino & Hut 1997; Bekki 1998; Finoguenov et al. 2003a); evaporation of the cold gas in disc galaxies via heat conduction from the surrounding hot ICM (Cowie & Songaila 1977; Fujita 2003); and a gradual decline in the SFR of a galaxy due to the stripping of halo gas (strangulation or suffocation; Larson, Tinsley & Caldwell 1980; Bekki et al. 2002; Kodama et al. 2001; Finoguenov et al. 2003b).

Among all of these, strong dynamical interactions such as cluster tidal forces and major interaction/merging of galaxies are less preferred since such processes distort the morphology of galaxies and cannot explain spiral arm structures in passive spiral galaxies.

Among the rest, since passive spirals exist in the environment with a local galaxy density of $\sim$ 1 Mpc^{-2} or at about the virial radius, those mechanisms that work in this environment are good candidates for the creation of passive spiral galaxies. Kodama et al. (2001) and Tanaka et al. (2004) discussed that plasma gas density is too low at the virial radius for ram-pressure stripping (of the cold gas in a galactic disc), concluding that stripping of hot halo gas is preferred to the stripping of cold gas. However, using the analytical model, Fujita (2003) showed that the cold gas stripping can be effective at around the virial radius at higher redshift (also see Fujita & Goto 2004). Mihos et al. (2003) proposed that infalling sub-groups may have high enough gas density to strip the cold gas.

Unfortunately, to further specify the responsible mechanisms is rather difficult. Any of the remaining mechanisms can work at the environment around the virial radius. Since most of the processes act over a period of a few Gyr, observations at one redshift cannot easily provide the detailed information that is needed to specify one process. It is also worth noting that E+A (post-starburst) galaxies (Dressler & Gunn 1983), which have been thought to be transition objects in cluster galaxy evolution, were found to have their origin in merger/interaction in the general field region (Goto et al. 2003d,e). And thus, explaining cluster galaxy evolution using E+A galaxies is not realistic anymore.

More importantly, Tanaka et al. (2004) found that the environmental dependence of galaxies properties is different for bright and faint galaxies. Faint galaxies ($M^* + 1 < M_r < M^* + 2$) have a break at the same environment as this work. On the other hand, bright galaxies ($M_r < M^*+1$) do not have a specific break in environmental dependence, and their properties monotonically change as a function of the environment. Goto et al. (2003a) found two breaks on the morphology-density relation. These results might be indicating that there may be two (or more) different physical processes at work, and that passive spiral galaxies may be the transition objects of only one physical mechanism among many.

However, discovering transition objects in a certain environment is one step forward compared with previous work. Since we now know what galaxies we should trace, observing the abundance and properties of passive spiral galaxies toward higher redshift clusters will bring further implications on the underlying physical mechanism. As a forerunner, Goto et al. (2004) identified a population of red, late-type galaxies rapidly changing morphology at $z \sim 0.17$. Among various semi-analytic simulations of cluster galaxy evolution (e.g., Okamoto & Nagashima 2001; Diaferio et al. 2001; Benson et al. 2001; Springel et al. 2001; Shioya et al. 2001,2002; Okamoto & Nagashima 2003), any that predict passive spirals as transition objects should be favored.

5 SUMMARY

We have performed a deep K band imaging of 32 passive spiral galaxies with the UKIRT, in order to answer the remaining two questions in the subject: (i) passive spirals are S0s or not; (ii) they are dusty starburst galaxies or not. Our results are summarized as follows.

- All 32 K band images of passive spiral galaxies with seeing of ~ 0.5 arcsec show clear spiral arm structures in the disc, except two unclear cases due to a nearby bright object. The distribution of the concentration parameter is different from that of early-type galaxies with more than 99.99% significance. We conclude that passive spirals are a different population of galaxies from S0s.
- Optical-infrared colour ($r - K$) of passive spiral galaxies is not redder than that of normal galaxies. Therefore, passive spiral galaxies are not likely to be dusty starburst galaxies.

Since our results support truly "passive" and "spiral" nature of these galaxies, it is very likely that passive spiral galaxies are indeed transition objects currently undergoing cluster galaxy evolution. Further study of passive spiral galaxies will have further implications for the physical mechanisms governing cluster galaxy evolution.

ACKNOWLEDGMENTS

We are grateful to Masayuki Tanaka and Sadanori Okamura for useful discussion. We thank the referee, Dr. Philip James for many insightful comments, which improved the paper significantly. We thank the UKIRT support astronomers and telescope operators for their help during the observation. The United Kingdom Infrared Telescope is operated by the Joint Astronomy Centre on behalf of the U.K. Particle Physics and Astronomy Research Council.

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