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Elliptical Galaxies with Emission Lines from the Sloan Digital Sky Survey *

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Abstract As part of a study of star formation history along the Hubble sequence, we present here the results for 11 elliptical galaxies with strong nebular emission lines. After removing the dilution from the underlying old stellar populations by use of stellar population synthesis model, we derive the accurate fluxes of all the emission lines in these objects, which are then classified, using emission line ratios, into one Seyfert 2, six LINERs and four HII galaxies. We also identify one HII galaxy (A1216+04) as a hitherto unknown Wolf-Rayet galaxy from the presence of the Wolf-Rayet broad bump at 4650 Å. We propose that the star-forming activities in elliptical galaxies are triggered by either galaxy-galaxy interaction or the merging of a small satellite/a massive star cluster, as has been suggested by recent numerical simulations.

Key words: Galaxies: elliptical and lenticular, cD – Galaxies: starburst – Galaxies: individual: A1212+06, A1216+04, CGCG13-83, IC 225

1 INTRODUCTION

The history of star formation in elliptical galaxies carries important information on their formation and evolution and provides invaluable constraints for cosmological models (Eggen, Lynden-Bell & Sandage 1962). In the conventional view, an elliptical galaxy was thought to be a simple stellar system with an old stellar population formed in a single star forming episode at a very early stage of the galaxy's history, which evolved quietly and passively ever since, with very few stars made in the past 1–2 Gyrs (Searle, Sargent & Bagnuolo 1973; Larson 1975). However, in recent decades a rival view has been proposed based on the hierarchical clustering model (White & Rees 1978; Kauffmann, White & Guiderdoni 1993), which requires that the most massive objects are formed at later times via merging smaller subunits. In this scenario, massive ellipticals are formed through merging of two spiral galaxies, and this has also been shown by numerical simulations (see the recent review by de Freitas Pacheco, Michard & Mohayaee 2003; Toomre & Toomre 1972; Barnes 1992; Barnes & Hernquist 1992; Bendo & Barnes 2000).

Recently, Fukugita et al. (2004) reported the discovery of active star-forming activities in the field elliptical galaxies in the Sloan Digital Sky Survey (SDSS). They found that the percentage of such star-forming elliptical galaxies in their sample is a few tenths of a percent and suggested that these star-forming ellipticals could be the progenitors of E+A galaxies, which are devoid of nebular emission lines but have very strong Balmer absorption lines superimposed on an old stellar population, and are interpreted as being the post-starburst ended within the last 1.5–2 Gyr (Couch

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& Shaples 1987; Barger et al. 1996). In this paper, we will present more examples of such elliptical galaxies which will show unambiguous evidence of young star-forming activities, found during our study of star formation history along the Hubble sequence.

This paper is organized as follows: in Section 2 we present a sample of 11 ellipticals with strong emission lines. In Section 3 we present the results of a stellar population synthesis, of using the standard BPT diagrams to classify the ionizing mechanism for these 11 ellipticals, and on the radial profiles, color distribution and star forming activities for three HII galaxies (A1212+06, A1216+04 and CGCG 13–83). A discussion is given in Section 4 and our conclusions are given in Section 5. Where required we adopt a Hubble constant of $H_0 = 75\,\mathrm{km\ s^{-1}\ Mpc^{-1}}$, $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$.

2 THE DATA

SDSS is the most ambitious astronomical (both photometric and spectroscopic) survey project ever undertaken (Gunn et al. 1998; Blanton et al. 2003). Recently, we cross-correlated the SDSS DR2 spectroscopic archive dataset with the Third Reference Catalogue of Bright Galaxies (RC3; de Vaucouleurs et al. 1991) by positional match at an accuracy of ~ 10 arcsec, and derived a sample of 1027 galaxies with both morphological classification and spectroscopic information. Of these, 48 sources are catalogued as Elliptical galaxies in RC3 with mean numerical index (T) of either –4 or –5. Our main target is to study the star formation activity along the Hubble sequence, which will be presented by Shi et al. (2005).

In this paper we show that among these 48 elliptical galaxies 11 objects clearly show strong nebular emission lines with Hα equivalent widths (EW) larger than 2 Å, and these are not classified before as AGNs either in the catalog of *Quasars and Active Galactic Nuclei* (Veron-Cetty & Veron 2003, 11th Ed.) or in any publications. The basic data of these 11 ellipticals are summarized in Table 1: the galaxy's name, coordinates, redshift, distance, absolute blue magnitude and morphological type.

Table 1 Parameters of 11 Elliptical Galaxies with Emission Lines from SDSS

Name	RA (2000) h m s	DEC (2000) ° ′ ″	Redshift z	Distance (Mpc)	M_B	Morphology
NGC 426	01 12 48.6	–00 17 24.6	0.0173	69.2	–20.4	E+
NGC 677	01 49 14.0	+13 03 19.1	0.0170	68.0	–21.0	E0
IC 225	02 26 28.2	+01 09 37.9	0.0051	20.4	–17.1	E0
CGCG 13–83	12 08 23.5	+00 06 36.9	0.0408	163.2	–21.2	E0
NGC 4187	12 13 29.2	+50 44 29.3	0.0305	122.0	–21.4	E0
A1212+06	12 15 18.3	+05 45 39.4	0.0067	26.8	–17.3	E0
A1216+04	12 19 09.8	+03 51 23.3	0.0051	20.4	–17.1	E0
NGC 4581	12 38 05.1	+01 28 39.9	0.0062	24.8	–18.8	E+
NGC 5216	13 32 06.9	+62 42 02.4	0.0979	39.2	–19.5	E0
IC 989	14 14 51.3	+03 07 51.3	0.0253	101.2	–21.3	E0
NGC 5846	15 06 29.1	+01 36 20.9	0.0057	22.8	–20.9	E0

3 RESULTS

In the study of emission-line spectra, an unavoidable issue is contamination from the underlying old stellar population, especially in the Balmer lines. The standard method is to use the stellar population synthesis model to fit the observed spectrum. Here we use the same stellar population synthesis code, STARLIGHT version 2.0 (Cid Fernandes et al. 2004) for all the 11 elliptical galaxies. We made the routine searches for the best linear combination of 45 Simple Stellar Populations (SSP) from the recent stellar population model of Bruzual & Charlot (2003) defined by three metallicities (0.2 $Z\odot$, $Z\odot$, and 2.5 $Z\odot$), and 15 different ages (0.001, 0.003, 0.005, 0.01, 0.025, 0.04, 0.10, 0.29, 0.64, 0.90, 1.4, 2.5, 5.0, 11 and 13 Gyr). The criterion of minimum χ square is used to define the best fit and the search for the best-fit parameters is carried out with a simulated annealing method,

Table 2 Emission Line Properties and Classifications for 11 Elliptical Galaxies

Galaxy	Flux (10^{-17} erg s^{-1} cm^{-2})							Type
	Hβ	[O III] λ4959	[O III] λ5007	[O I] λ6300	Hα	[N II] λ6583	[S II] λ6724	
A1212+06	3404.6	3809.3	11607.2	207.1	10013.9	829.0	1846.7	HII
A1216+04	4224.0	5648.2	16918.5	127.8	18514.3	914.1	1628.5	HII
CGCG 13–83	239.4	35.4	93.5	31.0	1017.8	454.3	270.2	HII
IC 225	862.6	331.5	994.6	90.2	3262.3	720.9	1008.4	HII
IC 989	171.4	97.9	349.0	302.5	698.8	931.6	914.1	LINER
NGC 4187	246.6	176.2	576.9	351.7	963.0	1720.0	1404.7	LINER
NGC 426	579.9	297.4	1099.2	910.8	2681.4	4708.7	2056.7	LINER
NGC 4581	909.0	2354.2	7203.8	405.8	3893.6	2310.0	1711.5	Seyfert
NGC 5216	124.7	67.3	306.0	238.3	588.7	509.8	626.3	LINER
NGC 5846	302.8	160.6	258.4	695.8	658.6	833.2	501.3	LINER
NGC 677	263.1	71.8	288.4	303.3	1069.2	979.5	1088.7	LINER

which consists of a series of 10^7 likelihood-guided Metropolis tours through the parameter space (see also Cid Fernandes et al. 2005).

After subtracting the best-fit model spectrum from the observed one, we obtain the pure emission-line spectrum, from which we could measure accurate fluxes for all the emission lines with the *specfit* or *onedspec.splot* task in IRAF [1]. The results are presented in Table 2. The errors in the line flux are typically around 5%. It is well known that we can distinguish narrow-line AGNs from normal star-forming galaxies by using emission line flux ratios, the so-called BPT diagrams (Baldwin, Phillips & Terlevich 1981; Veilleux & Osterbrock 1987). According to our measurement of the emission lines, we classify these 11 ellipticals into one Seyfert 2, six LINERs and four HII galaxies (see Fig. 1). We find that the three HII galaxies (A1212+06, A1216+04 and IC 225) are in fact dwarf galaxies with absolute B magnitudes (M_B) fainter than −18, as shown in Table 1. It is easy to understand the Seyfert and LINER activities in elliptical galaxies, since the host galaxies of the most powerful AGNs (quasars) are usually massive elliptical galaxies (Floyd et al. 2004). The recent discovery of a tight relation between bulge velocity dispersion and black hole mass strongly suggests that massive black holes are ubiquitous and scale with the bulge masses (Ho & Kormendy 2000; Tremaine et al. 2002). While the pure star-forming activities in elliptical galaxies are especially rare, the nature and triggering mechanism are still open questions. In the following we will concentrate on a detailed study of three star-forming galaxies (A1212+06, A1216+04 and CGCG 13–83). The fourth one (IC 225) was discovered by Gu et al. (2006) to be a compact dwarf elliptical galaxy with a peculiar blue core which contains two distinct nuclei, separated by 1.4 arcseconds. The off-nucleus core could be a dwarf galaxy or a halo cluster, swallowed by IC 225 and thus triggered the starburst activity in IC 225.

In Figure 2 we show the false-color RGB images of the four star-forming elliptical galaxies, which combined information from the *g*-, *r*- and *i*-band SDSS images according to the algorithm given by Lupton et al. (2004). In Figure 3 we plot their SDSS optical spectra, with enlargements of the higher-order Balmer absorption lines in the wavelengths of 3750–4150 Å shown in the insets of panels (a, c, d). The inset of panel (b) is an enlargement on the Wolf-Rayet blue bump around 4650 Å.

3.1 Radial Surface Brightness Distribution

The radial surface brightness distribution of ordinary elliptical galaxies typically follows the de Vaucouleurs $R^{1/4}$ law (de Vaucouleurs 1953). Since the SDSS photometrical survey at *u*- and *z*-bands are much shallower (Fukugita et al. 1996) and *i*-band used a thinned CCD, an instrumental effect known as the "red halo" in the PSF wings was reported to seriously affect the *i*-band

[1] IRAF is distributed by the National Optical Astronomical Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA), Inc., under a cooperative agreement with the National Science Foundation.

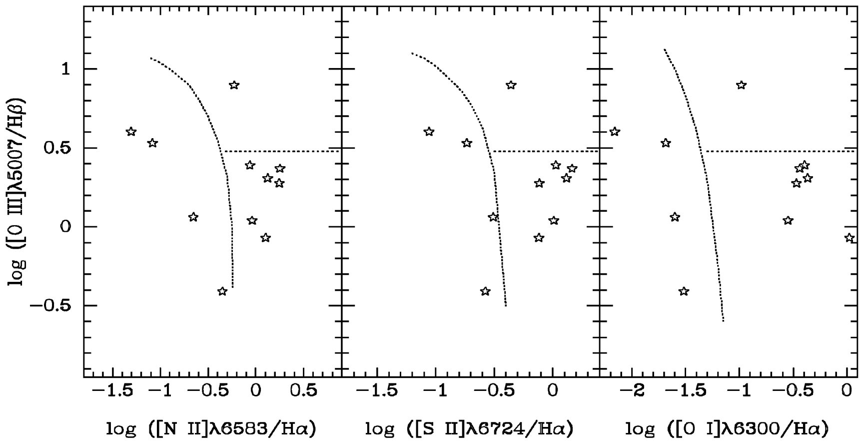

Fig. 1 Diagnostic diagrams. *left:* log([NII]λ6583/Hα) vs. log([OIII]λ5007/Hβ); *middle:* log([SII]λ6724/Hα) vs. log([OIII]λ5007/Hβ); *right:* log([OI]λ6300/Hα) vs. log([OIII]λ5007/Hβ). The dotted lines dividing narrow-line AGNs from starburst galaxies are taken from Veilleux & Osterbrock (1987).

Table 3 Fitting results with de Vaucouleurs $R^{1/4}$ law for A1212+06 and CGCG 13–83

Band	A1212+06			CGCG 13–83		
	μ_0 (mag arcsec^{-2})	r_e (arcsec)	rms	μ_0 (mag arcsec^{-2})	r_e (arcsec)	rms
g	7.6±0.3	0.83±0.06	0.07	13.6±0.1	5.2±0.3	0.06
r	8.8±0.4	1.2±0.1	0.09	13.1±0.1	5.3±0.3	0.07

photometric analysis (e.g., Wu et al. 2005). We will only derive the g- and r-band stellar surface brightness distributions by using the standard task *ellipse* in *IRAF*, for A1212+06 and CGCG 13–83. These are shown in Figure 4. The SDSS magnitude system (Fukugita et al. 1996) is quite similar to the AB system (Oke & Gunn 1983). The zero point of magnitude for each frame is obtained directly from the image header. For A1216+04, we do not apply the photometric measurement since it is a late-type blue compact dwarf (BCD) galaxy (Gordon & Gottesman 1981; Hoffman et al. 1987). The best fits with the de Vaucouleurs $R^{1/4}$ are shown as solid lines, the fitting results are summarized in Table 3. We find that the fitting is quite good with rms typically less than 0.1.

In order to derive the g–r color distribution, we first check the PSF profiles of g- and r-band images and then smooth the g-band image by convolving a Gaussian kernel to match the r-band PSF. In Figure 5 we show the g–r color distributions for A1212+06 and CGCG 13–83. It is very interesting to note that the two sources show different behaviors: for A1212+06, the nucleus is exceptionally blue, and the color becomes increasingly redder outwards, while for CGCG 13–83 the color distribution is nearly uniform, very similar to the compact elliptical galaxy IC 1639 (Wu et al. 2005) except for the inner ∼5 arcsecond region. This result indicates that their modes of star forming activity might be different.

3.2 Star Forming Activity

3.2.1 A1212+06

A1212+06 is a member of the Virgo cluster and was identified as an HII galaxy by Maza et al. (1991) using emission line ratios such as [O II]λ3727/[O III]λ5007, [N II]λ6584/Hα. Our stellar population synthesis fitting indicates that, 50% of the 4800 Å monochromatic radiation comes from

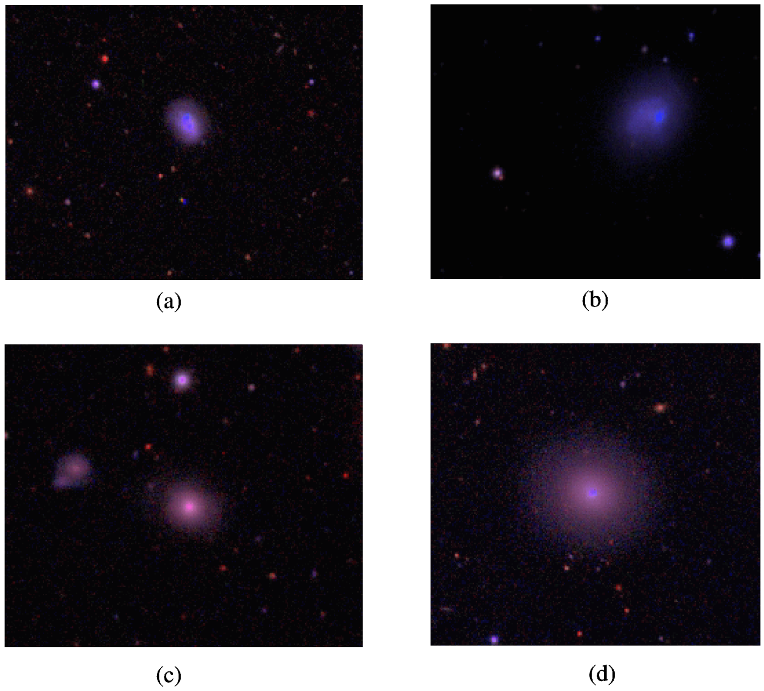

Fig. 2 False-color RGB images of four starburst galaxies, obtained from the (r, g, i) SDSS images with the method proposed by Lupton et al. (2004). (a) A1212+06, $3.5' \times 2.5'$; (b) A1216+04, $3.2' \times 2.5'$; (c) CGCG 13–83, $3.5' \times 2.8'$; (d) IC 225, $3.2' \times 2.8'$.

a young ($< 10^8$ yr) population, 38%, from an intermediate-aged ($10^8 <$ age $<10^9$ yr) population, and 12% from an old ($> 10^9$ yr) population.

We use the standard method to compute the nebular extinction, based on the Balmer decrement and assuming Case B recombination and a standard reddening law (Cardelli, Clayton & Mathis 1989). For A1212+06, the observed $F_{\mathrm{H}\alpha}/F_{\mathrm{H}\beta}$ is 2.94, the nebular extinction, A_V, is estimated to be 0.076 mag. Thus the extinction-corrected Hα luminosity, $L_{\mathrm{H}\alpha}^{\mathrm{corr}}$, is 9.3 $\times 10^{39}$ erg s^{-1}. Using the empirical calibration given by Kennicutt (1998), SFR$_{\mathrm{H}\alpha}$ is equal to 0.073 $M_\odot$ yr^{-1}, which we note only refers to the central 3 arcsecond region. At the same time, we could also estimate the SFR from the infrared (8–1000 μm) luminosity (Kennicutt 1998). The IR luminosity, $L_{8-1000\,\mu\mathrm{m}}$, calculated by using the fluxes taken from the IRAS Faint Source Catalog (Moshir et al. 1989), is equal to 9.11×10^{42} erg s^{-1} and the corresponding SFR$_{\mathrm{IR}}$ is 0.41 $M_\odot$ yr^{-1}, much larger than the value of SFR$_{\mathrm{H}\alpha}$, which suggests that star-forming activity is occurring in a larger area than the SDSS spectral fibre region, and is also confirmed by the g–r color distribution.

3.2.2 A1216+04

Like A1212+06, A1216+04 is an HII galaxy in the Virgo cluster (Terlevich et al. 1991). Stellar population synthesis fitting indicates that there is a significant contribution (86%) from the young stellar components to the total monochromatic flux at 4800 Å. This fraction is much larger than the one (50%) in A1212+06. The observed $F_{\mathrm{H}\alpha}/F_{\mathrm{H}\beta}$ is equal to 4.38, the corresponding nebulae extinction is 1.17 mag, and the SFR for the central $3''$ region is 0.21 $M_\odot$ yr^{-1}. It is very interesting to note that the SFR deduced from the IR emission is exactly the same as SFR$_{\mathrm{H}\alpha}$: this indicates that star-forming activity is very much concentrated in the region covered by the SDSS fibre. In

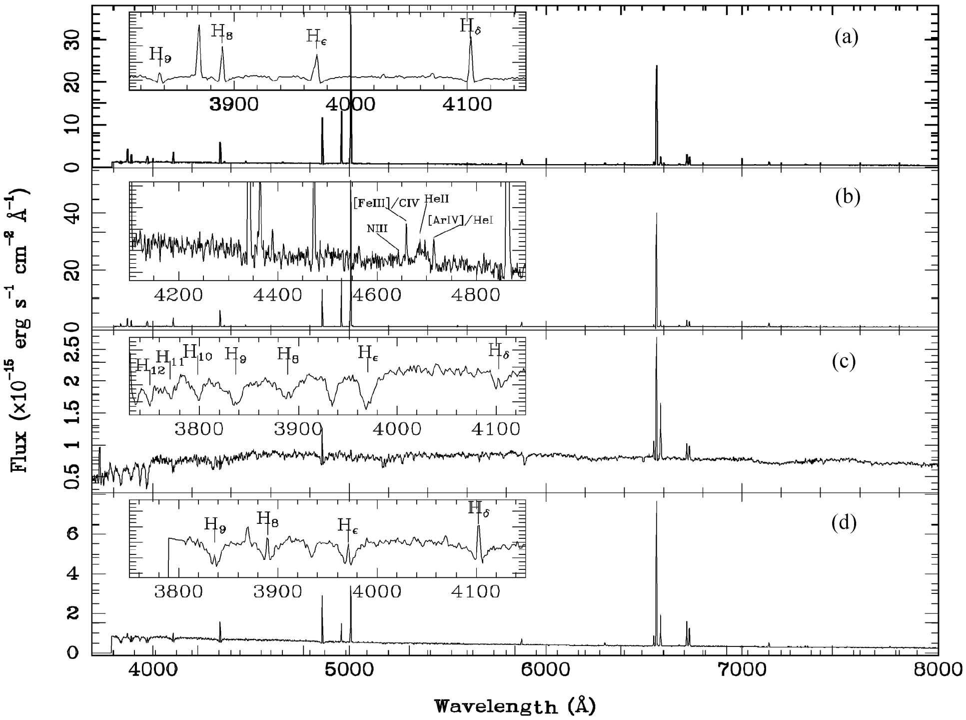

Fig. 3 Optical spectra of the starburst galaxies in our sample, taken from the SDSS. (a)A1212+06; (b) A1216+04; (c) CGCG 13–83; (d) IC 225. The insets of (a), (c) and (d) are enlargements of the wavelength range of 3750–4150 Å, where the higher-order Balmer absorption lines are positively detected. The inset of (b) is an enlargement of the W-R bumps around 4650 Å.

fact, this object was wrongly classified as an elliptical galaxy (Gordon & Gottesman 1981; Hoffman et al. 1987), and will be omitted from further analysis.

The spectrum of A1216+04 shows the broad bumps at 4650 Å (see the inset in Figure 2b) that are characteristic of W-R stars (Conti 1991). The bumps include stellar and nebular emission lines, He II λ4686, [Fe III] λ4658, N III $\lambda\lambda$4634–4641, [Ar IV] λ4711 and C IV λ4658. Thus we identify A1216+04 as a hitherto unknown Wolf-Rayet galaxy. However, the low S/N for the Wolf-Rayet features prevents us from further analysis.

3.2.3 CGCG 13–83

CGCG 13–83 was regarded as an elliptical galaxy with active star formation by Fukugita et al. (2004), who first found its strong Hα emission line. However, they did not do any further analyses such as stellar population synthesis or radial profiling: these we now do. The spectrum of CGCG 13–83 is displayed in Figure 3c, which clearly shows higher-order Balmer absorption lines in the wavelength range 3750−4150 Å, which have been taken as unambiguous evidence of intermediate-aged ($\sim 10^8$ yr) stellar populations (Gonzalez Delgado, Leitherer & Heckman 1999; Gonzalez Delgado, Heckman & Leitherer 2001). Our stellar population synthesis modeling confirms that 46% of the monochromatic flux at 4800 Å is due to the intermediate-aged ($10^8 <$ age $< 10^9$ yr) stellar components.

The observed $F_{\mathrm{H}\alpha}/F_{\mathrm{H}\beta}$ is equal to 4.25, the corresponding nebulae extinction is 1.09 mag, and the SFR for the central 3″ region is 0.07 $M_\odot$ yr^{-1}. All the results are summarized in Table 4.

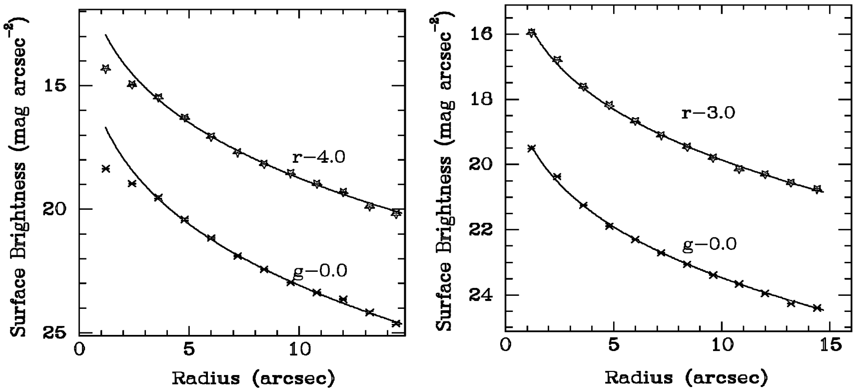

Fig. 4 Stellar surface brightness of SDSS images in two bands (g and r). The solid lines are the best fit with de Vaucouleurs $R^{1/4}$ law. The profiles are shifted for clarity. *Left panel:* A1212+06; *Right panel:* CGCG 13–83.

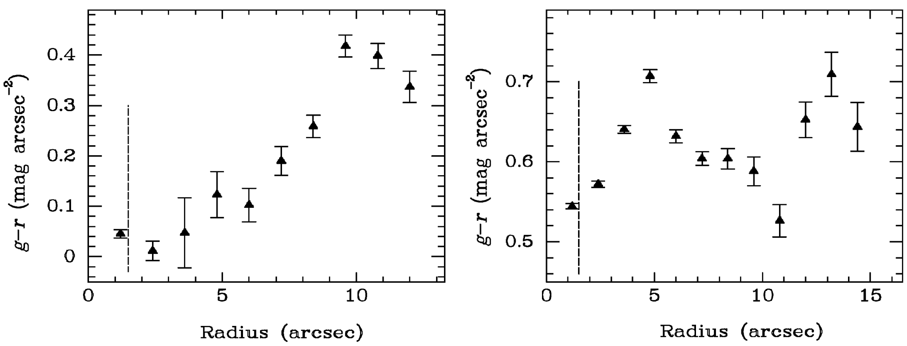

Fig. 5 The (g–r) color distributions of A1212+06 (left) and CGCG 13–83 (right). The vertical dashed line indicates the SDSS spectral fibre size.

Table 4 Nebula extinction, extinction-corrected H_α luminosity and star formation rate of three star-forming galaxies

Name	$A_V^{\rm nebular}$ (mag)	$L_{\rm H\alpha}^{\rm corr}$ (erg s^{-1})	SFR (H_α) ($M_\odot$ yr^{-1})	$L_{\rm FIR}$ (erg s^{-1})	SFR (FIR) ($M_\odot$ yr^{-1})
A1212+06	0.076	9.30×10^{39}	0.073	9.11×10^{42}	0.41
A1216+04	1.17	2.71×10^{40}	0.21	4.60×10^{42}	0.21
CGCG 13–83	1.09	8.83×10^{39}	0.070	...	...

Unlike A1212+06 and A1216+04, the [O III]$\lambda\lambda$4959, 5007 in CGCG 13–83 is rather weak and it can only be detectable after subtracting the best fit spectrum from the observed spectrum. However, the radial profiles can be fitted with the $R^{1/4}$ law very well for the g- and r-band images, as shown in the right panel of Figure 4.

4 DISCUSSION

By using images and spectra from the SDSS, we have investigated the emission line properties for a sample of 11 elliptical galaxies with emission lines picked out from 48 ellipticals by cross-correlating the SDSS DR2 with RC3 catalog. We identified four HII galaxies: one (A1216+04), is in fact a late-type BCD and a new Wolf-Rayet galaxy, another two (A1212+06 and IC 225) are dwarf ellipticals, and the other one (CGCG 13–83) is an ordinary elliptical. Recently, Guzman et al. (2003) and Graham (2005) found that dwarf ellipticals form a continuous extension, both chemically and dynamically, of the more luminous (ordinary) ellipticals. If we simply regard A1212+06 and IC 225 as normal ellipticals, then, for our sample, the frequency of star-forming ellipticals is $3/47 = 6.38\%$, significantly higher than the value $2/210 \approx 1\%$ given by Fukugita et al. (2004). The difference is probably caused by our selection criteria, the small sample size and problems of morphological classification in RC3 (de Souza, Gadotti & dos Anjos 2004).

It is well known that bar, galaxy-galaxy interaction and merger are efficient mechanisms to trigger starburst activities for spiral galaxies (Huang et al. 1996; Zou et al. 1995). Since the star-forming elliptical galaxies are rather rare, the most probable mechanism for triggering starburst in the ellipticals is still an open question. Worthey (1997) suggested that the most promising mechanisms to trigger nuclear starbursts in elliptical galaxies include interaction, major mergers and minor mergers (accretion events with satellite less than 10% of the galaxy's mass). Major mergers are mergers of two disc galaxies of comparable mass, and Mihos & Hernquist (1996) showed using numerical simulations, that starburst activities during such a merger could be two orders of magnitude higher than that in isolated galaxies and can be sustained for from several 10^7 yr to $\sim 2 \times 10^8$ yr after the collision. It could be the case for many infrared luminous galaxies, which are found to show morphological peculiarities indicative of encounters, such as multiple nuclei, tidal tails, loops, and shells (Sanders et al. 1988; Sanders 1992). Though major mergers trigger the most powerful starburst, they are less common than minor mergers with the satellite less than 10% of the galaxy's mass. Ostriker & Tremaine (1975) and Tremaine (1981) showed that for a typical galaxy, irrespective of morphological type, several tens of percent of its mass has probably been accreted in the form of discrete subunits. Hernquist & Mihos (1995) showed by numerical simulation minor mergers between gas-rich disk galaxies and less massive dwarf galaxies.

For CGCG 13–83, the light distribution is very smooth, and there is not any sign of interacting remnant, such as tidal tails. However, when we searched the 30 arcmin view field of the NASA/IPAC Extragalactic Database (NED), we detected two galaxies that possibly interact with CGCG 13–83. One is CGCG 13–84 (RA: $12^{\rm h}08^{\rm m}31.3^{\rm s}$, Dec: $+00°08' 11''$; z: 0.034942), about $2.5'$ northeast of CGCG 13–83, and of 15.2 mag (g-band). The other is SDSS J120828.48+000948.7 (RA: $12^{\rm h}08^{\rm m}28.490^{\rm s}$, Dec: $+00°09' 48.90''$; z: 0.03539), about $3.4'$ northwest and of 17.3 mag (g-band). So, according to the criteria proposed by Schmitt (2001), CGCG 13–84 is most probably a physical companion of CGCG 13–83. Meanwhile, previous numerical simulations have indicated that gas inflows occur within one dynamical timescale (a few $\times\ 10^8$ yr) of the initial collision (Barnes & Hernquist 1991; Mihos et al. 1992, 1993). Both have suggested that the triggering mechanism for star forming activity in CGCG 13–83 is due to the interaction with CGCG 13–84.

In the case of A1212+06 the morphology is also very smooth. However, when we inspected the central region carefully, we found two distinct cores in its RGB image. Because the SDSS spectrum carries no spatial information, we cannot examine the nature of the cores. Long-slit optical spectroscopy is under consideration for this object.

5 CONCLUSIONS

In this paper, we studied a sample of 11 elliptical galaxies with emission lines. After removing old stellar contribution and using standard classification criteria, we identified one Seyfert 2, six LINERs and four HII galaxies. For the four HII galaxies, we found that one (A1216+04) is a new Wolf-Rayet galaxy, two (A1212+06, IC 225) are ellipticals with two distinct nuclei, and CGCG 13–83 is possibly interacting with CGCG 13–84. We propose that the star-forming activities in elliptical galaxies could be triggered by either galaxy-galaxy interaction or the merging of a small satellite/a massive star cluster.

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