TWO PHYSICALLY DISTINCT POPULATIONS OF LOW-IONIZATION NUCLEAR EMISSION-LINE REGIONS

J. WANG, J. Y. WEI, AND P. F. XIAO

National Astronomical Observatories, Chinese Academy of Science, Datun 20A, Chaoyang District, Beijing, 100012, China; wj@bao.ac.cn

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ABSTRACT

The nature of low-ionization nuclear emission-line regions (LINERs) has been an open question for a long time. We study the properties of LINERs from several different aspects. The LINERs are found to consist of two different categories that can be clearly separated in the traditional Baldwin–Phillips–Terlevich diagrams, especially in the [O i]/Hα versus [O iii]/Hβ diagram. LINERs with high [O i]/Hα ratios (Population I) differ from ones with low ratios (Population II) in several properties. Broad emission lines are only identified in the spectra of Population I LINERs. While only the Population II LINERs show luminous infrared emission and occurrence of core-collapse supernovae in the host. Combining these results with the known distribution of stellar populations not only suggests that the two populations have different line-excitation mechanisms, but also implies that they are at different evolutionary stages.

Key words: galaxies: active – galaxies: fundamental parameters – galaxies: nuclei

1. INTRODUCTION

Low-ionization nuclear emission-line regions (LINERs) are frequently identified in the local universe: different surveys show that up to one-third of all galaxies show LINER-like spectra (see Ho 2008 for a recent review). Comparing with Seyfert 2 galaxies and star-forming galaxies, optical spectra of LINERs are dominated by the emission lines of low-ionized species, such as [O i]λ6300, [O ii]λ3727, [S ii]λλ6716, 6731 and [N ii]λλ6548, 6583 (e.g., Heckman 1980). Emission-line ratios are frequently used to classify different emission-line galaxies with distinct power sources. At present, the classification of emission-line galaxies is commonly based on the empirical Baldwin–Phillips–Terlevich (BPT) diagrams that were originally proposed by Baldwin et al. (1981), and then refined by Veilleux & Osterbrock (1987). Theoretical and empirical demarcation lines were proposed by Kewley et al. (2001) and Kauffmann et al. (2003) to separate star-forming galaxies on the BPT diagrams, respectively. Kewley et al. (2006) recently proposed a new empirical classification scheme that separates Seyferts and LINERs.

However, LINERs are diverse in their observational properties. Ho et al. (1993) identified a group of LINER/H II "transition objects" with relatively low [O i]/Hα ratios compared with "pure" LINERs. They proposed that the LINER/H II objects are most likely composite systems that contain a LINER plus an H II region. Many studies found that these "transition" LINERs differ from the "pure" ones in their stellar population distributions (e.g., Cid Fernandes et al. 2004; Kewley et al. 2006). Wang & Wei (2008) and P. F. Xiao et al. (2009, in preparation) show that all their broad-line LINERs are associated with large [O i]/Hα ratios and old stellar populations.

The physical origin of LINERs has long been the subject of hot debate. The photoionization by the central active galactic nuclei (AGNs) is suggested to be the main power source in some LINERs (e.g., Ferland & Netzer 1983). The AGN origin is strongly supported by the detection of broad emission lines in optical spectra (e.g., Ho et al. 1997; Wang & Wei 2008). Other evidence supporting the AGN origin includes the hard X-ray spectra (e.g., Terashima et al. 2000; Flohic et al. 2006), and UV variability (e.g., Maoz et al. 2005). On the other hand, LINERs could be explained by other excitation mechanisms unrelated to an AGN, such as fast shocks (e.g., Dopita et al. 1997; Lipari et al. 2004), post-AGB stars (Binette et al. 1994), or low-mass X-ray binaries (e.g., Eracleous et al. 2002; Flohic et al. 2006).

At present, these results imply that the current classification scheme results in a hybrid LINER population (different power sources or evolution stages). In this Letter, we study the classification scheme through several different approaches, and show that the currently classified LINERs consist of two populations that can be clearly separated on the BPT diagrams. The two distinct populations might have different physical origins, and be at different evolutionary stages.

2. BROAD-LINE LINERS: A ZONE OF AVOIDANCE IN THE BPT DIAGRAMS

Wang & Wei (2008) and P. F. Xiao et al. (2009, in preparation) systematically searched for partially obscured AGNs from the MPA/JHU SDSS DR4 catalog (Heckman & Kauffmann 2006 and references therein) according to the existence of broad Hα emission in the spectra. Figure 1 shows the distributions of these partially obscured AGNs on the three commonly used BPT diagrams. The objects from Wang & Wei (2008) and from Xiao et al. are displayed by the red solid and open squares, respectively. Indeed, the detection of broad Hα emission is strongly affected by the contamination of diffuse light from the old stars. A large effect is expected in the SDSS spectra, especially for weak nuclear emission, since the spectra are obtained by a relatively large fiber aperture (3”). The nearby broad-line LINERs identified in the Palomar spectroscopic surveys (Ho et al. 1997) are therefore included to avoid the bias. These objects are shown in Figure 1 by the blue circles.

Based on the combined sample, although it is not clear in the [O iii]/Hβ versus [N ii]/Hα diagram, a remarkable zone of avoidance (ZOA) is obviously found in the other two diagrams, especially in the [O iii]/Hβ versus [O i]/Hα diagram, for the

1 Xiao et al. searched for partially obscured AGNs from the galaxies (the median S/N per pixel ⩾ 30) located above the Kauffmann demarcation line according to measurements given in the MPA/JHU catalog by the same method described in Wang & Wei (2008).

2 The partially obscured AGNs are selected if Fw/σc ⩾ 3, where Fw is the stellar continuum subtracted flux averaged over the rest frame wavelength range from 6500 to 6530 Å, and σc is the standard deviation of flux within wavelength region between 5980 and 6200 Å.
Figure 1. Three diagnostic BPT diagrams. The solid lines show the theoretical demarcation lines separating AGNs from star-forming galaxies proposed by Kewley et al. (2001), and the long-dashed line the empirical line proposed in Kauffmann et al. (2003). The empirical separation scheme of LINERs suggested by Kewley et al. (2006) is drawn by the dot-dashed lines in the [S\textsc{ii}]/H\alpha vs. [O\textsc{iii}]/H\beta and [O\textsc{i}]/H\alpha vs. [O\textsc{iii}]/H\beta diagrams. The red squares show the partially obscured AGNs selected from the MPA/JHU catalog (solid squares represent objects from Wang & Wei (2008), and open ones from P. F. Xiao et al. 2009, in preparation). The broad-line LINERs identified in the Palomar spectroscopic surveys are plotted by the blue circles (Ho et al. 1997). The short-dashed lines show the proposed boundaries of the broad-line LINERs drawn by eyes. We define the LINERs located above the boundaries as Population I LINERs, and ones below the boundaries as Population II LINERs.

broad-line LINERs. The nondetection of broad H\alpha in the objects within the ZOA cannot be caused by the increasing contribution of young stars, both because young stars show less contamination caused by the stellar absorptions at the H\alpha region and because Seyfert galaxies have stellar population ages younger than LINERs (see Figure 11 in Kewley et al. 2006). We examined the high-quality spectra of LIRGs (Cao et al. 2006) located in the ZOA one-by-one by eye, and the results reinforce the nondetection of broad H\alpha. The ZOA naturally suggests that the previously defined LINERs likely consist of at least two types of galaxies with distinct power sources. In each panel, we define an empirical lower boundary for these broad-line LINERs by eye, and plot the boundary by a short-dashed line. The regions above and below the line is defined as Zone A and B for short, respectively.

3. WHAT IS IN THE ZOA?

The lack of broad-line LINERs naturally motivates us to suspect that the LINERs in Zone B are powered by the ionizing radiation arising from some stellar processes unrelated to an AGN. The host properties are investigated in two aspects in this section: infrared (IR) emission and occurrence of core-collapse supernovae (cc-SNe).

3.1. Ultra-Luminous/Luminous IR LINERs

Cao et al. (2006) established a large sample of luminous IR galaxies (LIRGs, defined as $L_{\text{IR}} > 10^{11} L_{\odot}$) through the cross-identification of the SDSS DR2 with the catalogs of the Infrared Astronomical Satellite (IRAS) survey. Figure 2 shows the distributions of the sample on the three BPT diagrams. The LIRGs are shown by the cyan solid and open triangles for the IRAS faint and point sources, respectively. As an additional test, the ultraluminous IR galaxies (ULIRGs, $L_{\text{IR}} > 10^{12} L_{\odot}$) identified in the IRAS 1 Jy sample (Kim & Sanders 1998; Veilleux et al. 1999) are overplotted in Figure 2 by the blue stars.

As done in Section 2, we focus on the [O\textsc{iii}]/H\beta versus [S\textsc{ii}]/H\alpha and [O\textsc{iii}]/H\beta versus [O\textsc{i}]/H\alpha diagrams. The diagrams clearly show that all the IR luminous LINERs are remarkably clustered in the Zone B defined previously, except only a few outliers.

3.2. LINERs: Occurrence of cc-SNe

The occurrence of cc-SNe is an indicative of young and intermediate-aged stellar populations. The cc-SNe are believed to be produced by the explosion of massive stars ($\geq 8$–10 $M_{\odot}$) at the end of their life time ($\sim 10^7$–$10^8$ yr). We cross-match the SDSS DR6 with the SAI–SDSS image SN catalog originally done by Prieto et al. (2008). The sample finally contains the SDSS spectra of host galaxies (central $3''$ of 51 type Ib/c and 182 type II SNe). We remove the absorption features from the spectra through the principle component analysis technique as described in Wang & Wei (2008). The emission-line fluxes
Figure 2. Same as Figure 1 but for different samples. The cyan solid and open triangles show the LIRGs that are identified by cross-matching the SDSS DR2 with the IRAS faint and point sources, respectively (Cao et al. 2006). The ULIRGs from Veilleux et al. (1999) are drawn by the blue stars. Note that almost all the LINERs with luminous IR emission are below the boundaries suggested in this Letter. The galaxies selected by the occurrence of cc-SNe are plotted by the red circles (solid for SNe II and open for SNe Ib/c). Among these galaxies, only rare events are located in the region of the Population I LINERs.

are then measured by the direct integration on the starlight-subtracted spectra. The distributions of these galaxies on the three BPT diagrams are plotted in Figure 2. As the results are the same as given previously, the LINERs selected by the occurrence of cc-SNe are mainly located in Zone B.

4. COMPARISON BETWEEN THE TWO POPULATIONS OF LINERS

The above statistical study indicates that the currently classified LINERs could be obviously separated into two categories on the traditional BPT diagrams. The separation is most remarkable in the [O i]/Hα versus [O iii]/Hβ diagram: (1) Population I LINERs within Zone A have large [O i]/Hα ratios; (2) Population II LINERs within Zone B have low [O i]/Hα ratios. The two populations show distinct observational properties that are compared with each other in Table 1. In addition to the observational properties described above, the two populations are also different in their host stellar population ages. The stellar population is found to be on average younger in Population II LINERs than in Population I LINERs (e.g., Kewley et al. 2006; Wang & Wei 2008; Cid Fernandes et al. 2004; Gonzalez Delgado et al. 2004; Sarzi et al. 2005).3

The distinct observational properties imply that the two population LINERs have different excitation mechanisms. For the Population I LINERs, one naturally expects that the gas is photoionized by the ionizing radiation arising from the central accretion disk due to the detection of the broad lines in their spectra. Not as luminous AGNs, a weak ionizing radiation (log U ~ −3 to −4) with a hard spectrum is required to explain the emission-line spectra of LINERs (e.g., Kewley et al. 2006; Lewis et al. 2003; Sabra et al. 2003; Gabel et al. 2000). Indeed, the hard X-ray spectra are observed in some LINERs by different instruments (e.g., Flohic et al. 2006; Gliozzi et al. 2008; Rinn et al. 2005). The low level and hard ionizing radiation is consistent with the predictions of the advection dominated accretion model (e.g., Abramowicz et al. 1995; Narayan & Yi 1995) in which the inefficient radiation results in a hot accretion disk. Finally, the nondetection of luminous IR emission and cc-SNe in the objects could be interpreted by both weak accretion activity and aged stellar population.

The explanation of the excitation mechanism is, however, nontrivial for the Population II LINERs. The nondetection of broad lines in their spectra implies that they are plausibly related to the stellar processes (see also in Ho 2008). Comparisons of

Table 1 Comparison of the Observational Properties Between the Population I and II Liners

| Properties          | Population I | Population II |
|---------------------|--------------|---------------|
| [O i]/Hβ            | High         | Low           |
| Broad lines         | Yes          | No            |
| Stellar population  | Old          | Relatively young |
| IR emission         | No           | Yes           |
| Core-collapse SNe   | No           | Yes           |

3 The over detected young stellar population in the “transition” LINERs was recently argued against by Ho (2008). The author believes that the over detection rate might be caused by the Hubble-type bias.
X-ray and optical observations show an anomalous high Hα emission for the “transition” LINERs (e.g., Ho 2008; Terashima & Wilson 2003; Flohic et al. 2006). The fast shock model could be excluded at first because the observed UV high excitation emission lines are always lower than the predicted ones (e.g., Gabel et al. 2000; Maoz et al. 1998). The young star cluster model (Barth & Shields 2000) requires extremely young stellar populations and sizable Wolf–Rayet stars that are, however, not observed (e.g., Ho et al. 2003). The “transition” LINERs are suspected to be composite systems that consist of a LINER and an H ii region component, which, however, cannot explain the nondetection of broad emission line in the Population II LINERs.

The LINER-like spectra can be ionized by evolved, low-mass stars. The spectral synthesis model shows that the ionizing photon is dominated by the emission from the post-AGBs after \( \sim 10^8 \) yr since the burst (Binette et al. 1994). A simple calculation recently done by Ho (2008) suggests that the post-AGB stars within the center of galaxies can provide sufficient ionizing photons in the “transition” LINERs. In particular, the post-AGB star models predict a low [O i]/Hα ratio (< 0.5) for reasonable parameters (Binette et al. 1994; Stasińska et al. 2008), which is quantitatively in agreement with the current boundary separating the Population I and II LINERs. The post-AGB star model is also consistent with the observed IR properties. One of the characteristic features of post-AGB stars are their strong IR excess. We estimate the IR luminosity for individual post-AGB star as \( L_{\text{IR}}/L_\odot = 1.77 f (r/pc)^2 (T_d/K)^4 \) in two fiducial cases: \( r = 0.01 \) pc, \( T_d = 200 \) K and \( r = 0.1 \) pc, \( T_d = 80 \) K (Suarez et al. 2006), where \( r \) is the distance from the dust shell to star, \( T_d \) is the temperature of the dust, and \( f = 0.004 \) is the emissivity of the dust (Draine & Lee 1984). The total IR luminosity from the dust is then \( L_{\text{IR}} = L_{\text{IR}}^* (M/M_\odot) \), where \( M \) and \( M_\odot \) is the integrated post-AGB star mass and mass of individual post-AGB star (i.e., \( M_\odot = 1–8 \) M_\odot). Adapting the typical integrated stellar mass of galaxy center \( \sim 2 \times 10^9 \) M_\odot and the Salpeter initial mass function results in a roughly estimated integrated IR luminosity \( \sim 10^{10.7–12} L_\odot \), which is (marginally) in agreement with the definition of LIRGs (ULIRGs). Note that the estimated IR luminosity should be strictly regarded as an upper limit because the exact value strongly depends on star formation history of galaxy. Finally, the occurrence of cc-SNe in the Population II LINERs provides evidence in timescale supporting the post-AGB star model. As massive stars explode at the end of their lifetimes \( \sim 10^7.5 \) yr, the low- and intermediate-mass stars (1–8 M_\odot) evolve to the AGB and post-AGB phase at the end of their main sequence lifetimes with an upper limit \( \sim 5 \times 10^7 \) yr.

5. IMPLICATIONS ON AGN’S EVOLUTION

We briefly discuss the implications on the AGN’s evolutionary scenario in the context of the coevolution of AGN and its host galaxy. Some recent studies suggest a delay (with timescale \( \sim 100 \) Myr) between the onset of the star formation and the subsequent intensive black hole accretion (e.g., Davies et al. 2007; Kawakatu et al. 2003; Granato et al. 2004). In this scenario, the emission lines might be dominantly excited by the massive starburst at the very beginning of an AGN activity. The central accretion nucleus is either obscured (e.g., Hopkins et al. 2005, Wada & Norman 2002) or too weak to maintain a broad-line region (BLR) (e.g., Laor 2003; Xu & Cao 2007; Nicastro et al. 2003; Elitzur & Shlosman 2006). The accretion activity might increase within the first a few of \( 10^8 \) yr as the very young circumnuclear stellar population ages (Davies et al. 2007). After the first a few of \( 10^8 \) yr, when the AGN is still buried or weak, the emission lines are dominantly excited by the ionizing radiation from post-AGB stars (i.e., the Population I LINER phase). Sturm et al. (2006) indicated that IR-bright LINERs have intermediate PAH feature ratios (12.7 \( \mu \text{m}/11.2 \mu \text{m} \) and 6.2 \( \mu \text{m}/11.2 \mu \text{m} \)) between H ii region and IR-faint LINERs. At this phase, the post-AGB stars contribute the luminous IR emission, and the evolved massive stars explode at the end of their lives. A luminous AGN subsequently appears, and shines with decreasing Eddington ratio as the stellar population continuously ages (Wang & Wei 2008; Kewley et al. 2006). After the luminous phase, the AGN evolves to a less luminous stage with hard ionizing radiation (i.e., Population I LINER phase). The underlying very old stellar population becomes dominant because the importance of the young stellar population fades out entirely.

6. SUMMARY

The previously defined LINERs are found to consist of two categories that can be clearly separated in the traditional BPT diagrams, especially in the [O i]/Hα versus [O iii]/Hβ diagram. Population I LINERs are defined to have higher [O i]/Hα ratios than Population II LINERs. The two population LINERs differs in the presence of broad emission lines in their spectra, strength of IR emission, host galaxy stellar population age, and occurrence of cc-SNe. These different properties suggest that the two populations not only have different line excitation mechanisms, but also are at different evolution stages.

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