

TESTING THE EVOLUTIONARY SEQUENCE BETWEEN HIDDEN BROAD LINE REGION (HBLR) AND NON-HBLR SEYFERT 2 GALAXIES WITH THE 4000-Å BREAK STRENGTHS

PO-CHIEH YU*[†]

Graduate Institute of Astronomy, National Central University, Chung-Li 32054, Taiwan

E-mail: pcyu@astro.ncu.edu.tw

KUI-YUN HUANG

Institute of Astronomy and Astrophysics, Academia Sinica, P.O. Box 23-141, Taipei 10617,

Taiwan

E-mail: ljhuang@asiaa.sinica.edu.tw

CHORNG-YUAN HWANG

Graduate Institute of Astronomy, National Central University, Chung-Li 32054, Taiwan

E-mail: hwangcy@astro.ncu.edu.tw

YOUICHI OHYAMA

Institute of Astronomy and Astrophysics, Academia Sinica, P.O. Box 23-141, Taipei 10617,

Taiwan

E-mail: ohyama@asiaa.sinica.edu.tw

We compared the 4000 Angstrom break (D4000) strength of hidden broad line regions (HBLR) and non-HBLR Seyfert 2 galaxies. Previous studies showed that only about 40% – 45% of Seyfert 2 galaxies show HBLR. The reason of the non-detection of HBLR in some Seyfert 2 galaxies is still under debated. Our results show that the D4000 strength of the non-HBLR Seyfert 2 galaxies is larger than that of HBLR ones, implying that the non-HBLR Seyfert 2 galaxies have older stellar population in the nuclear regions. This suggests that there might be an evolutionary connection between the non-HBLR and HBLR Seyfert 2 galaxies. The gas around the nucleus of the non-HBLR Seyfert 2 galaxies might have diminished in the older age, which would cause low accretion rates. When the accretion rate is below some thresholds, the broad line regions could disappear.

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1. INTRODUCTION

Seyfert galaxies are radio-quiet active galactic nuclei (AGNs) and further divided into two subtypes, Seyfert 1 and Seyfert 2 galaxies. According to the unification model[1], Seyfert 2 galaxies are suggested to be the same objects as Seyfert 1 but viewed from an edge-on direction. The broad-line region (BLR) of Seyfert 2 galaxies is obscured by a dusty torus and thus only forbidden emission lines can be observed. Photons from BLRs could be scattered by electrons and thus that might be detectable by the polarimetry in Seyfert 2 galaxies. Previous studies indicated that some Seyfert 2 galaxies did show polarized broad permitted emission lines. The discovery of the hidden broad-line region (HBLR) further supported the unification model.

However, previous polarimetry survey showed that only about 40% – 50% of Seyfert 2 galaxies exhibit HBLRs[2]. The non-detection of the HBLRs in some Seyfert 2 galaxies challenges the unification model. The reason causing the non-detection of HBLRs is still under debated. Several possibilities have been proposed: (1) Based on the ratio of f_{25}/f_{60} , Heisler et al. (1997)[3] suggested that the detectability of the HBLR in Seyfert 2 galaxies is related to the orientation of the torus. (2) Some evolutionary processes might be at work between HBLR and non-HBLR Seyfert 2 galaxies[2][4]. (3) Zhang & Wang (2006)[5] found that non-HBLR Seyfert 2 galaxies and narrow line Seyfert 1 galaxies (NLS1s) have similar distribution of black hole masses, accretion rate and the ratio of f_{25}/f_{60} . Non-HBLR Seyfert 2 galaxies were thus suggested to be the counterparts of NLS1s at an edge-on orientation. (4) Non-HBLR Seyfert 2 galaxies might be powered by nuclear starbursts rather than accretion onto the central black hole[6]. (5) Shu et al. (2007)[7] showed that the the visibility of polarized broad lines might be affected by nuclear activity and obscuration. (6) Some Seyfert 2 galaxies could intrinsically lack broad line regions[8]. (8) Some Seyfert 2 galaxies might be deficient in scattering material.

Yu & Hwang (2011)[9] discovered that the $[\text{N II}]/\text{H}\alpha$ ratios of non-HBLR Seyfert 2 galaxies are higher than those of HBLR Seyfert 2 galaxies. They suggested that the difference could be caused by different evolutionary stages of starburst activities in non-HBLR and HBLR Seyfert 2 galaxies. We estimate the 4000-Å break ($D_n(4000)$) strengths[10] of these galaxies to further investigate the age of the stellar population around the nuclei of the HBLR and non-HBLR Seyfert 2 galaxies. The $D_n(4000)$ strength is an indicator that provides reliable estimates for the ages of stellar populations[11]. The elements contributing to the opacity are usually ionized metals. $D_n(4000)$ is caused by absorption of high energy radiation from metals in stellar atmospheres. The $D_n(4000)$ strength is thus small for young, blue stars and large for old, metal-rich ones .

2. OBSERVATIONS

Nine Seyfert 2 galaxies were observed using a 1.8-m telescope, with a low-resolution spectrograph and a long-slit at the Bohyunsan Optical Astronomy Observatory (BOAO) in South Korea. The observations were carried out over three multi-day periods: 2011 October 27–31; 2012 January 9–12; and 2012 May 3–7. Approximately 5.5 observable nights had a seeing of 2'' – 3''. Using a 150 groove per mm grating and a slit width of 2.9'', we covered a wavelength range of 3500–7500Å at a spectral resolution of $\lambda/\delta\lambda \sim 366$. Using the IRAF package, we then follow the standard data reduction procedure, i.e., flat-fielding, wavelength calibration, and flux calibration. The spectra of

16 additional Seyfert 2 galaxies were also obtained from the Sloan Digital Sky Survey (SDSS), as well as the spectrum of NGC 3079 from the NASA/IPAC Extragalactic Database (NED). We estimated the $D_n(4000)$ strengths of 10 HBLR and 16 non-HBLR Seyfert 2 galaxies.

3. RESULTS AND DISCUSSION

The optical spectra of the HBLR Seyfert 2 galaxies showed weak stellar absorption lines. However, the spectra of the non-HBLR Seyfert 2 galaxies showed strong 4000-Å break and stellar absorption lines, such as the G band near 4300 Å and the magnesium features near 5200 Å. We then estimate the $D_n(4000)$ strength to conduct a quantitative comparison. The $D_n(4000)$ index was originally defined by Bruzual (1983)[12] and redefined by Balogh et al.(1999)[10] to reduce the reddening effects:

$$D_n(4000) = \frac{\int_{4000}^{4100} f_\lambda d\lambda}{\int_{3850}^{3950} f_\lambda d\lambda}.$$

We removed the contamination of emission lines in our measurements of the $D_n(4000)$ strengths. Figure 1 shows the $D_n(4000)$ strengths and the spectral index Fe5270 of the 10 HBLR and 16 non-HBLR Seyfert 2 galaxies. Both the Kolmogorov-Smirnov test ($P = 99.1\%$) and Student's T -test ($P = 99.6\%$) show that the $D_n(4000)$ distribution of the HBLR and non-HBLR Seyfert 2 galaxies are significantly different, indicating they have different stellar populations. The $D_n(4000)$ can be separated with $D_n(4000) = 1.2$. Except for three sources, NGC 5347, NGC 5929, and NGC 5252, the $D_n(4000)$ strengths of most HBLR Seyfert 2 galaxies are smaller than those of non-HBLR galaxies. These three HBLR Seyfert 2 galaxies were previously classified as non-HBLR Seyfert 2 galaxies[2][13] and only found to show HBLRs with the Keck telescope[14][15]. Therefore, the HBLRs in these three sources are substantially weaker than those in the other HBLR Seyfert 2 galaxies. This implies that the visibility of HBLRs is related to $D_n(4000)$ strengths. Based on the simple stellar population models[16], the corresponding stellar age of $D_n(4000) = 1.2$ is approximately 2.5×10^8 years. These results indicate that the stellar ages of the majority of the non-HBLR Seyfert 2 galaxies are older than several 10^8 years. This observation is also consistent with the overabundance of nitrogen in the non-HBLR Seyfert 2 galaxies, which can be explained by the evolution of starburst activities in these Seyfert 2 galaxies[9].

The $D_n(4000)$ strength might be affected by the observed sizes or the Hubble types of the galaxies. Because the aperture of SDSS ($3''$) is similar to the slit width of our observation ($2.9''$), we compared the distance distribution in our sample. The average distance of the HBLR and non-HBLR galaxies is 62.2 and 58.5 Mpc respectively. Both the Kolmogorov-Smirnov test ($P = 9.1\%$) and Student's T -test ($P = 16.3\%$) show that the distance distributions of the HBLR and non-HBLR Seyfert 2 galaxies are similar. Our results indicate that there is no apparent relation between distance and $D_n(4000)$ strength. These results are unlikely to have been caused by the aperture effect. We also investigate the effects of Hubble type of the host galaxies. The stellar ages around the nuclei would naturally be different if the HBLR and non-HBLR Seyfert 2 galaxies have different types of host galaxies. We use a numerical Hubble type proposed by De Vaucouleurs to compare the morphology of our samples. There is no relation between the Hubble type and the $D_n(4000)$ strength measured within the nuclear regions. Whether the host galaxies are early or

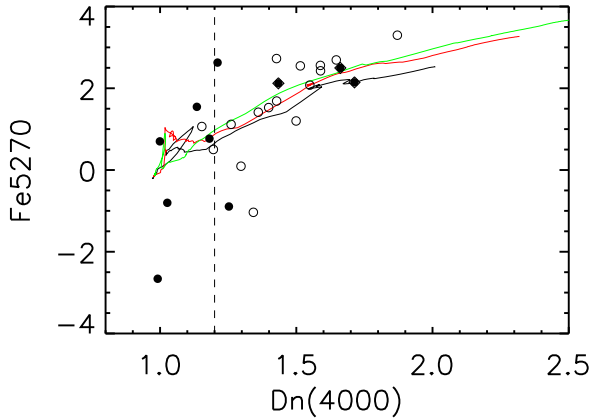


Figure 1: The $D_n(4000)$ strengths and the spectral index Fe5270 of the 10 HBLR and 16 non-HBLR Seyfert 2 galaxies. Symbols: filled circle – HBLR Sy2s; open circle – Non-HBLR Sy2; Diamonds – weak HBLRs: NGC 5347, NGC 5929, and NGC 5252. The lines show the evolution of the stand simple stellar population models[16] at ages from 10^5 to 10^{10} yr for the mentalicities (Black: $Z = 0.008$; Red: $Z = 0.02$; Green: $Z=0.05$). The $D_n(4000)$ strength of the non-HBLR Seyfert 2 galaxies is larger than that of HBLR galaxies, indicating that the stellar population of non-HBLR galaxies is older than that of HBLR galaxies.

late types, the $D_n(4000)$ strengths of the non-HBLR Seyfert 2 galaxies are larger than those of the HBLR galaxies.

Our results show that the stellar population of the non-HBLR Seyfert 2 galaxies is older than that of HBLR galaxies. Storchi-Bergmann et al. (2000)[17] and González Delgado et al. (2001)[18] have shown that nuclear starbursts might be a general phenomenon in Seyfert galaxies. Storchi-Bergmann et al. (2001)[19] further suggested that a composite Seyfert 2 + starburst nucleus might evolve into a pure Seyfert 2 nucleus with an old stellar population. Our results suggest that the state of HBLR and non-HBLR galaxies might represent different evolutionary stages of star formation. We propose a potential evolutionary scenario for Seyfert galaxies. When certain mechanisms, such as nuclear bars[20] or merger processes transport material from outer regions to feed AGNs, gas accumulates in the nuclear regions and triggers star formation. During this period, galaxies could be dominated by AGNs as well as star formation activities (i.e., Seyfert 1 and HBLR Seyfert 2 galaxies). However, when the specified mechanisms stop transporting material, the power of AGNs declines and the BLRs might vanish. In the occurrence of this event, the nucleus then becomes a pure Seyfert 2 nucleus with an evolved stellar population (i.e., non-HBLR Seyfert 2 galaxies).

The scenario predicts the potential development of two different populations of non-HBLR Seyfert 2 galaxies. When Seyfert 1 and HBLR Seyfert 2 galaxies evolve into non-HBLR galaxies, the original orientations of the torus should remain preserved. In the other words, a Seyfert 1 nucleus evolve into a "face-on" non-HBLR nucleus, and a HBLR Seyfert 2 nucleus evolves into an "edge-on" non-HBLR Seyfert 2 nucleus. This suggests that some non-HBLR Seyfert 2 galaxies might actually have a face-on orientation without heavy obscuration. This prediction is consistent with the outcome of a hydrogen column density distribution of non-HBLR Seyfert 2 galaxies; taken

from a large sample of 120 Seyfert 2 galaxies (49 HBLR and 71 non-HBLR) compiled by Wu et al. (2011)[4], we note that 40% of non-HBLR Seyfert 2 galaxies are unabsorbed; that is, N_H less than 10^{22} cm^{-2} . Conversely, only 60% of non-HBLR Seyfert 2 galaxies are absorbed, whereas a higher fraction of HBLR (83%) galaxies have a column density larger than 10^{22} cm^{-2} . Tran et al. (2011)[8] discovered some "naked" non-HBLR Seyfert 2 galaxies that exude X-ray variability, but intrinsically lack BLRs. We suggest that these naked non-HBLR Seyfert 2 galaxies belong to the face-on non-HBLR galaxies.

4. SUMMARY

Overall, our results suggest that (1) the stellar population of the non-HBLR Seyfert 2 galaxies is older than HBLR galaxies, suggesting that there might be an evolutionary process; (2) the ages of nuclear region stellar populations is unrelated to the morphology of host galaxies; and (3) Seyfert 1 and HBLR Seyfert 2 galaxies might respectively evolve into unabsorbed and absorbed non-HBLR Seyfert 2 galaxies. The optical variability of the "face-on" non-HBLR Seyfert 2 galaxies might be detectable. This possibility can be tested in future observations.

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