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学 位 論 文 要 旨
Dissertation Summary

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論　文　名: (Dissertation Title) Ionization mechanism and ISM properties of the NLR in low-z and high-z AGNs

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Galaxy evolution is one of the most discussed topics in contemporary astronomy. The process, however, is yet to be fully understood due to the complex mechanisms involved. Physical and chemical properties of the interstellar medium (ISM) in galaxies and their redshift evolution are important to understand the formation and evolution of galaxies. The emission-line diagnostics is a powerful tool to investigate these properties. Active galactic nuclei (AGNs) are one of the most luminous objects in the Universe. Their host galaxies are mainly massive galaxies and have an active supermassive black hole (SMBH) powered by mass accretion at the center. In particular, spectroscopic properties of narrow-line regions (NLRs) in AGNs have been often investigated because NLR gas clouds distribute at ~kpc scale that is comparable to the spatial scale of host galaxies. Since NLR clouds are mostly ionized through the photoionization process, ISM properties of host galaxies can be studied through detailed comparisons between photoionization models and emission-line spectra of NLRs.

AGNs are also known to play an important role in the evolution of their host galaxies, which is so-called "AGN feedback". The AGN feedback is a negative/positive feedback effect on the star-formation activity in AGN host galaxies. Understanding the feedback process caused by AGNs is one of the most key issues to reveal the co-evolution of galaxies and SMBHs in addition to formation of massive galaxies.

The ISM properties of massive galaxies at $z > 2$ are particularly interesting, because it is sometimes claimed that the evolution of massive galaxies had already been completed at such high redshift. From statistical studies, metallicity of these galaxies are close to the values of local galaxies (thus close to the solar metallicity), and no redshift evolution is seen from $z \sim 2$ to present. This means that massive galaxies had been mainly formed at $z > 2$. However, normal massive-galaxies at $z > 2$ are too faint to be examined in detail. On the other hand, emission-line spectra of NLRs in AGNs offer an alternative approach to investigate the ISM properties of

high-z massive galaxies. In Chapter 2, we present the rest-UV spectra of three radio galaxies at $z \sim 3$ observed with VLT/FORS2 to measure the flux of several emission lines including relatively faint ones such as O III]λ1665, N IV] λ1486, and [Ne IV] λ2424. In addition, we collect UV-emission line fluxes of 12 high-z radio galaxies (HzRGs) from the literature. We diagnose the physical and chemical properties of the ISM for each object through the comparison between the measured emission-line fluxes and detailed photoionization models. We confirm that the metallicity of NLRs in AGNs at $z \sim 3$ is close to or higher than the solar metallicity, without assuming the gas density and ionization parameter thanks to the newly detected faint emission lines. This result suggests that HzRGs have already chemically matured by $z \sim 3$, that corresponds to the cosmic age of only ~ 2 Gyr.

The AGN feedback process is now considered to be important in the host galaxy evolution. However, its physical mechanism (i.e., how the AGN activity transmits its energy to the ISM) is still unclear. Clarifying the physical mechanism of its energy transmission (from the AGN to its surrounding ISM) is central to understand the feedback process. In Chapter 3, we here aim to disentangle the ionization mechanisms by the AGN—photoionization versus shock ionization, and to investigate the origin of the shock. It is widely believed that the dominant ionization mechanism of NLRs in AGNs is the photoionization by ionizing photons from the central engine. Recent careful observational and theoretical researches, however, gradually revealed the contribution of the fast shock as well as the photoionization, both as an ionization source of gas in NLRs. Such fast shocks in NLRs are possibly related to the AGN feedback and therefore it is interesting to explore whether and how the fast shock contributes the NLR ionization in AGNs. To observationally discriminate the ionization mechanism of gas clouds in NLRs, the flux ratio of two forbidden emission lines seen in J-band, [Fe II]1.257μm/[P II]1.188μm, is useful. The flux ratio of [Fe II]/[P II] in shock-excited regions is expected to be high (> 20), while that in purely photoionized clouds should be low (< 2). We report our near-infrared spectroscopic observations of 26 nearby Seyfert galaxies with a near-infrared spectrograph (ISLE) boarded on the 188 cm telescope at Okayama Astrophysical Observatory. As a result, we measured the [Fe II]/[P II] flux ratio or its lower limit for 19 objects and also collected the flux ratio for 22 Seyfert galaxies from the literature. Based on the collected data, we found that the NLRs are photoionized in most cases, but the fast shock contributes significantly in some Seyfert galaxies. The measured [Fe II]/[P II] flux ratio shows no correlation with the radio loudness of the Seyfert galaxies in our sample, indicating that the radio jet is not the main origin of fast shocks in NLRs of Seyfert galaxies. A possible candidate of the origin of fast shocks in NLRs is an AGN-driven outflow that is recognized as blueshifted and/or broad (FWHM > 1000 km s^{-1}) forbidden emission lines observed in low/high z AGNs. This outflow likely spreads out to ~ 1 kpc from the central AGN, given that the shocks in NLRs originates from such outflow. This work has been published in Terao et al. (2016).

In this thesis, we investigate the formation and evolution of galaxies by focusing on emission lines from NLRs in AGNs. From Chapter 2, we confirmed that HzRGs had been chemically matured by $z \sim 3$, by using the photoionization models with much smaller assumption comparing for previous works thanks to many emission lines. This result indicates that the epoch of formation such massive galaxies are mainly at $z \geq 4$. The inferred gas density and ionization parameter of NLRs tend to be higher than those seen in NLRs of low-z type 2 AGNs. This suggests that the properties of the ISM in NLRs possibly evolve with redshift.

From Chapter 3, we find that more than half of Seyfert galaxies in our sample show consistent [Fe II]/[P II] flux ratio with the prediction by the photoionization model (~ 2). Three Seyfert galaxies, NGC 2782, NGC 5005, and Mrk 463, however, show very

large [Fe II]/[P II] flux ratios ($\gtrsim$ 10), suggesting a significant contribution of the fast shock in the NLR excitation. The [Fe II]/[P II] flux ratio in our sample shows no clear correlation with the radio loudness or the strength of the starburst, suggesting that the radio jet and starburst are not the primary origins of the fast shocks in the NLR. These results infer that the shock heating associated with the AGN outflow can be an important mechanism to affect the surrounding ISM during the AGN feedback.