ngVLA will spatially pin-down mBHs and jets in optically-faint radio-loud galaxies

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Abstract

Understanding the mechanism on the formation of the massive black holes (mBHs), and growing process into the super-massive black hole mass regime ($M_{\rm BH} > 10^6 M_\odot$) is one of the most important studies in extragalactic astronomy. Recent Subaru/Hyper Suprime-Cam (HSC) discovered a large fraction of the VLA/FIRST 1.4 GHz radio sources, including optically-faint radio galaxies down to $g_{\rm AB} \sim 26$. This population covers a new parameter space of extremely radio-loud galaxies (ERGs) with radio-loudness parameter of $\log \mathcal{R}_{\rm rest} = \log(f_{\rm 1.4GHz,rest}/f_{g,\rm rest}) > 4$. Combination of the IR studies revealed that ERGs exhibit a high specific black hole accretion rate, reaching the order of the Eddington limit and some of them might reside in low-mass galaxies with $\log(M_\star/M_\odot) < 10$. The intrinsic radio-loudness ($\mathcal{R}_{\rm int}$), defined by the ratio of jet power over bolometric radiation luminosity, is one order of magnitude higher than that of radio quasars. This suggests that ERGs harbor a unique type of active galactic nuclei (AGN) that show both powerful radiations and jets, and possibly in a slim disk phase. Thanks to the superb sensitivity and resolution of the ngVLA, it will map the ~ 10 pc scale radio image, separating the radio core and jet structures of super-Eddington AGN as well as witnessing the effect of their feedback to the host galaxies up to $z < 3$. Its supreme spatial resolution also enable us to pin down the location of the mBHs in the host galaxies, evaluating the possibilities of wondering BH scenarios in those low stellar-mass ERGs.

Key words: quasars: supermassive balck holes —galaxies: active — galaxies: nuclei

1. Introduction

Understanding the properties of the massive black holes (mBHs) in the center of low-mass galaxies ($M_\star < 10^{10} M_\odot$) and their growing path of mBHs into the SMBHs is important to constrain the different mBH-seed formation/growing scenarios; direct collapse and/or super-Eddington accretion from the massive stars (Volonteri 2010). However, it is still unclear that how much fraction mBHs exist (so called occupation fraction) in such low-mass galaxies (Greene et al. 2020).

This motivates BH hunters to search mBHs in the low-mass galaxies using multi-wavelength data; optical spectroscopy using broad Hα emission (e.g., Greene & Ho 2004; Greene & Ho 2007; Xiao et al. 2011), narrow emission line ratios (e.g., Barth et al. 2008; Reines et al. 2013), mid-IR ($W1 - W2$) colors in *WISE* (e.g., Satyapal et al. 2014), X-ray observations (e.g., Mezcua et al. 2016; Chen et al. 2017; Kawamuro et al. 2019), as well as through studies of the AGN flux variability based on the properties that lower luminosity AGN have stronger variability amplitude (e.g., Morokuma et al. 2016; Baldassare et al. 2018; Kimura et al. 2020). On the other hand, radio surveys have rarely been used for searching massive BHs in low-mass galaxies since most of the local radio galaxies are found in the most massive system with $M_\star \sim 10^{12} M_\odot$, which would not host the mBHs considering the scaling relation (Kormendy & Ho 2013).

2. Radio and optical surveys as mBH finding machine

Recent Subaru/Hyper Supreme Cam (HSC) strategic survey has discovered > 3000 optically-faint counterparts of the radio bright VLA/FIRST radio continuum surveys, at $z \sim$ 0–3 (Yamashita et al. 2018), which is named as **WERGS** project. The WERGS survey has improved the optical counterpart fraction rate of the FIRST sources from $< 30\%$ (Ivezić et al. 2002) to $> 60\%$ (Yamashita et al. 2018). Figure 2 shows that WERGS sample covers very optically-faint RGs down to $g_{\rm AB} \sim 26$ and a wide range of radio-loudness parameter $\mathcal{R}_{\rm rest} = f_{\rm 1.4GHz}/f_{g\ \rm band}$ (e.g., Ivezić et al. 2002), opening the new parameter space of radio galaxies: extremely radio-loud galaxies (ERGs) with $\log \mathcal{R}_{\rm rest} > 4$. Such ERGs were undetectable in the previous SDSS surveys because of their shallow sensitivity down to only $g_{\rm AB} \sim 22$, suggesting a unique population we have never explored. Combining the multi-wavelength data covering the optical, IR, and radio band for the $\sim 10^3$ WERGS sample, Toba et al. 2019 derived IR-based physical parameters such as star-formation rate (SFR; from far-IR), stellar-mass ($M_\star$; from near-IR), as well as the AGN luminosity ($L_{\rm AGN,bol}$; from mid-IR).

Based on these derived quantities, Ichikawa et al. 2021 summarized interesting properties of the ERGs. The first important one is that all ERG are in the star-forming or starburst phase reaching specific star-formation rate of sSFR $\sim 10^{-8}$ yr^{-1}, suggesting that ERGs are in a rapid stellar-mass assembly phase with mass doubling times of ~ 100 Myr.

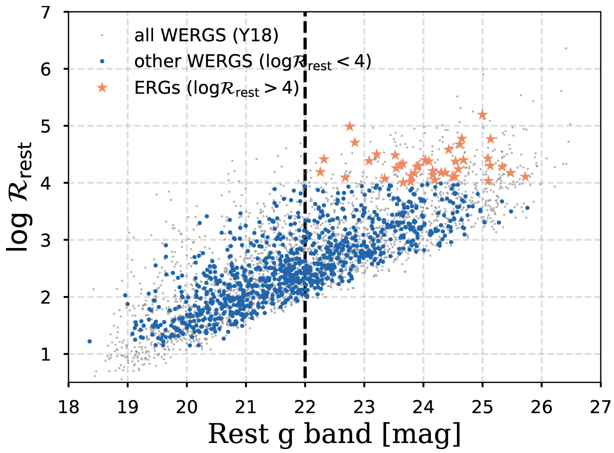

Fig. 1. $\log \mathcal{R}_{\rm rest}$ versus rest g band magnitude of the WERGS sample. The all WERGS sample (gray dots), the WERGS sample with IR detections (blue points) and the ERGs with IR detections (the sample with $\log \mathcal{R}_{\rm rest} > 4$; orange stars) are shown. $\mathcal{R}_{\rm rest}$ is defined as a ratio of the rest-frame 1.4 GHz flux density and the g-band one. Subaru/HSC survey discovered large number of very optically-faint ($g > 22$), and extremely radio-loud galaxies with $\log \mathcal{R}_{\rm rest} > 4$. The figure is taken from Yamashita et al. 2018 and Ichikawa et al. 2021.

The second important feature is visualized in the left panel of Figure 3 that IR detected ERGs are in a rapid BH accretion phase with high specific black hole accretion rate (sBHAR) with the expected Eddington ratio $\langle \log \lambda_{\rm Edd} \rangle \approx -0.4$, and some ERGs may be experiencing a super-Eddington phase. Besides, their stellar mass is relatively small, including the low-mass galaxies with $M_\star < 10^{10} M_\odot$.

The third one is illustrated in the right panel of Figure 3 that sources with higher $\mathcal{R}_{\rm rest}$ tend to have both higher sBHAR (which is conventionally defined as sBHAR $= L_{\rm AGN,bol}/M_\star$ erg s^{-1} $M_\odot^{-1}$ and thus it is a good indicator of $\lambda_{\rm Edd}$; see Mullaney et al. 2012) and higher intrinsic radio-loudness $\mathcal{R}_{\rm int}$, which is defined by the $\mathcal{R}_{\rm int} = L_{\rm jet}/L_{\rm AGN,bol}$; an energy balance of jet power over bolometric radiation luminosity. This paints a different picture of radio galaxies compared to conventionally known local radio galaxies with low $\lambda_{\rm Edd}$. ERGs represent a population of unique radio galaxies characterized by both high $\lambda_{\rm Edd}$ and high radio power.

3. Revealing Jet Properties of super-Eddington accretion: Test of slim-disk model

ERGs contains a population whose accretion disk state is in a possible super-Eddington phase associating with the radio jet (Ichikawa et al. 2021). One possible origin of this high production efficiency of radiation and jets is that the accretion disk of ERGs is actually in the "radiatively inefficient" state, but the physical origin of radiative inefficiency is different from the disks in the local radio galaxies. For example, the ERGs may be undergoing more rapid mass accretion (so called slim disk model; Abramowicz et al. 1988). Recent radiation hydrodynamical simulations suggest that when the mass accretion rate significantly exceeds the Eddington rate, radiation is effectively trapped within the accreting matter and advected to the central BH before escaping by radiative diffusion. As a result, the emergent radiation luminosity is saturated at the order of $L_{\rm Edd}$ (i.e., $\eta_{\rm rad} \lesssim 0.1$ at $\gg \dot{M}_{\rm Edd}$) and the accretion flow turns into a radiatively inefficient state even with a super-Eddington accretion rate (e.g., Ohsuga et al. 2005; Inayoshi et al. 2016). This phase is considered to be a key process of the BH seed growth in the high-z ($z > 6$) universe to describe the already known massive high-z SMBHs (e.g,. Bañados et al. 2018), and ERGs are promising low-z candidates of such an interesting population.

The ngVLA will provide us the first observational test on the physics of such slim disk model by observing possibly super-Eddington phase ERGs. Figure 4 shows the expected resolution by ngVLA. This shows the resolution could reach down to ~ 1 mas, which corresponds to < 10 pc in physical scale at $0.5 < z < 3$, that covers most of our targets sources. Since our target is the radio core and jet lobe, relatively higher frequency band at 2.4 GHz and 16 GHz would be the most suitable band sets, which is not suffered by the self-absorption of the core. With this superb resolution, ngVLA will spatially resolve the core and jet, and will constrain the radio core flux for the first time for the AGN with super-Eddington phase. Obtaining the radio core flux by ngVLA, and combining the AGN luminosities, the intrinsic radio-loudness $\mathcal{R}_{\rm int}$ and the jet efficiency $\eta_{\rm jet}$ can be obtained without the contamination of the radio lobe.

4. AGN feedback in low-mass ($\log M_\star/M_\odot < 10$) ERGs

Another important study of ERGs to be explored by ngVLA is on the effectiveness of AGN feedback in the low-mass galaxies. In recent years, the theoretical study of AGN feedback has been extended to low-mass galaxies (Silk 2017). This was motivated mainly by the increasing number of intriguing observational results showing signs of AGN feedback in low-mass galaxies (e.g., Mezcua et al. 2019). The reported jet power of $L_{\rm jet} > 10^{44}$ erg s^{-1} in ERGs is equivalent to that produced from radio quasars and local radio AGN residing in massive galaxies (Best et al. 2005). On the other hand, low stellar-mass ERGs are still in a starburst phase, indicative of a substantial gas reservoir, and lacking clear signatures of negative AGN feedback.

To investigate whether such a negative feedback from the jet is effective in the host galaxies, it is necessary to obtain high spatial resolution radio images that resolve the host galaxy down to scales of < 10 kpc (Reines et al. 2020). The spatial compactness of radio sources from VLA/FIRST with a spatial resolution of ~ 5 arcsec only provide poor upper-bounds of the radio jet size of < 40 kpc at $z \sim 1$. ngVLA will revolutionize this thanks to its supreme spatial resolution, which reaches down to < 100 pc at 2.4 GHz, and < 10 pc at 16 GHz. This over one-order-of-magnitude better resolution enables us to directly compare the jet location and the gas reservoir in the image, and to investigate the effect of the jet on the host galaxy.

5. Pinning Down the radio core: Test of wondering BHs in ERGs

Recently, Reines et al. 2020 employed the radio-survey approach to search for massive BHs by using VLA/FIRST and conducting VLA high spatial resolution follow-up observations

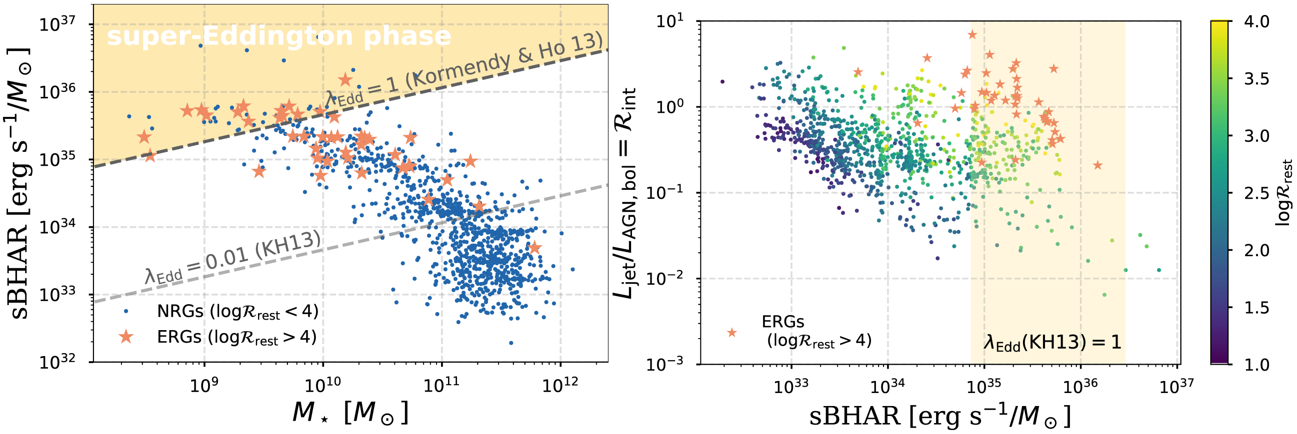

Fig. 2. (**Left**) The relation between sBHAR and $M_\star$. The sBHAR is conventionally defined as $\mathrm{sBHAR} = L_{\rm AGN,bol}/M_\star$ erg s^{-1} $M_\odot^{-1}$, an indicator of Eddington ratio $\lambda_{\rm Edd}$. The two dashed lines are the expected Eddington limits $\lambda_{\rm Edd} = 1$ and $= 0.01$ using the scaling relation of (Kormendy & Ho 2013). The orange shaded area represents the region of super-Eddington phase. (**Right**) The relation between $L_{\rm jet}/L_{\rm AGN,bol} = \mathcal{R}_{\rm int}$ and sBHAR. The yellow shaded area represents the corresponding $\lambda_{\rm Edd} = 1$ region assuming the scaling relation of (Kormendy & Ho 2013). The symbols are same as in Figure 1, but NRGs are shown with color gradation based on $\mathcal{R}_{\rm rest}$ in the range of $1 < \log\mathcal{R}_{\rm rest} < 4$. Both figures are taken from Ichikawa et al. 2021.

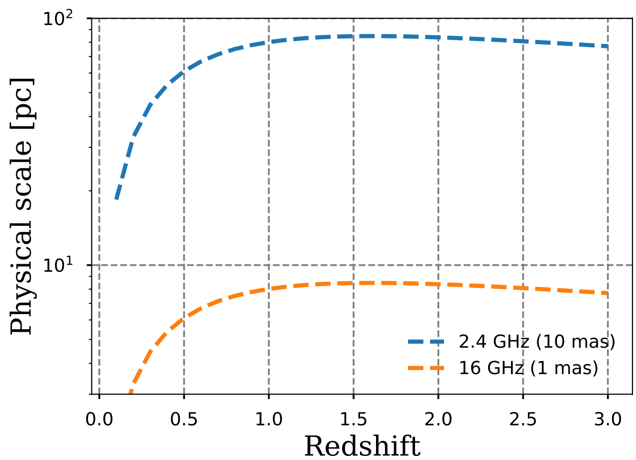

Fig. 3. Achievable resolution with ngVLA. Our main target bands are 2.4 GHz and 16 GHz, whose best resolution is at 10 mas (< 100 pc) and 1 mas (< 10 pc), respectively.

of local dwarf galaxies at $z < 0.1$, and found more than 10 candidates. One remarkable result was that most radio cores were not located at the center of the host, but off-nucleus, a possible signature of a previous merger. If the detection of an off-nucleus core is indeed the consequence of a galaxy merger, it indicates that the orbital decay of a black hole through dynamical friction is inefficient in this BH mass range, resulting in a population of BHs that fail to reach the galactic center within a Hubble time, since major mergers in dwarf galaxies becomes rare at $z < 3$ (e.g., Fitts et al. 2018), which is called a "sinking problem". Currently there are many theoretical implication regarding the existence of wandering BHs (e.g., Comerford & Greene 2014; Tremmel et al. 2018).

Considering that some ERGs are low-mass galaxies, they are important targets hosting such wondering BHs. High spatial resolution radio imaging by ngVLA can pin down the locations of such wandering BHs up to $z \sim 3$ since the radio core can be spatially separated from the jet lobes. Another advantage of the ngVLA observation is that it can reach sensitivities in a short (<1 hr[1]) exposures and contamination from X-ray binaries would be negligible considering its luminous radio luminosity for ERGs. Furthermore, with its long baselines, contamination from star formation can be minimised by selecting only point-like radio emission. Therefore, large-scale statistical studies of ERGs would provide insights into the frequency and environment of wandering BHs as a function of redshift and stellar-mass.

6. Strategy of Sample construction of ERGs in the era of ngVLA

The small number density of ERGs (~ 1 source deg^{-2}) and their optical faintness of $i_{\rm AB} \sim 25$ suggest that ERGs were easily missed in previous optical surveys of radio sources. Ichikawa et al. 2021 showed that ERGs can be discovered with wide (> 100 deg^2) and deep ($i_{\rm AB} \lesssim 26$) optical follow-up observations of radio sources. The number of known ERGs will increase in near future, once the Subaru/SSP survey is complete, covering an area of $\sim 10^3$ deg^2. The upcoming Subaru/Prime Focus Spectrograph (Takada et al. 2014) will conduct extensive optical and near-IR spectroscopic follow-up observations in the footprint of the HSC-SSP field, providing spec-z information of ERGs with $i_{\rm AB} \lesssim 24$. The forthcoming LSST survey (Ivezić et al. 2019) will cover half of the sky, and it will also increase the number of sources by another order of magnitude, resulting in $\sim 10^4$ sources. A significant fraction of these ERGs will also be expected to reside in low-mass galaxies. In the radio survey side, VLA/FIRST gives the most

[1] Since WERGS sample is selected from VLA/FIRST sources, their 1.4 GHz radio emission is very bright, with > 1 mJy. The ngVLA 1 hr integration time could reach the flux limit of 0.5 μJy/beam at 2.4 GHz and 0.26 μJy/beam at 16 GHz, respectively. If we assume a typical flux density of $f_\nu = 5$ mJy with the spectral index of $\alpha = -0.7$ with $f_\nu \propto \nu^\alpha$, S/N$=28$ (2.4 GHz) and S/N$=14$ (16 GHz), which is enough for our study.

important population since our targets are high radio-loudness values of $\log \mathcal{R}_{\rm rest} > 4$. In addition, the ongoing VLASS (Lacy et al. 2020), which will achieve a sensitivity down to 0.1 mJy at 2–4 GHz, giving an order of magnitude deeper radio observations than VLA/FIRST. This would increase the sample in addition to the traditional VLA/FIRST survey. Therefore, the combination of wide area (either shallow or deep) radio and deep optical imaging and spectroscopic surveys will give us a statistically large number of massive BH candidates in the era of ngVLA.

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