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AGN Feedback and its Importance to Galaxy Evolution in the Era of the ngVLA

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Abstract. Energetic feedback by Active Galactic Nuclei (AGN) plays an important evolutionary role in the regulation of star formation (SF) on galactic scales. However, the effects of this feedback as a function of redshift and galaxy properties such as mass, environment and cold gas content remain poorly understood. The broad frequency coverage (1 to 116 GHz), high collecting area (about ten times higher than the Karl G. Jansky Very Large Array), and superb angular resolution (maximum baselines of at least a few hundred km) of the proposed next-generation Very Large Array (ngVLA) are uniquely poised to revolutionize our understanding of AGN and their role in galaxy evolution.

Keywords. galaxies: active, galaxies: jets, galaxies: evolution

1. Introduction

A key missing element in our understanding of cosmic assembly is the nature of energetic feedback from supermassive black holes (SMHBs) and the impact of active galactic nuclei (AGN) on galaxy evolution. Energetic feedback produced by Active Galactic Nuclei (AGN) is believed to play an important role in galaxy evolution through the regulatory effect it may have on the star formation rate and efficiency of the host galaxy. Despite its importance, identifying AGN-driven feedback in action is observationally challenging and requires high sensitivity, high angular resolution, and broad frequency coverage. As a result, large-scale studies of jet-driven AGN feedback using existing radio telescopes, such as the Karl G. Jansky Very Large Array (VLA) and Atacama Large Millimeter and Submillimeter Array (ALMA), have not been feasible. With its unprecedented current reference design consisting of $\sim$214 $\times$ 18m antennas operating from 1 to 116 GHz with baselines out to several hundred km, the next-generation Very Large Array (ngVLA) will overcome current observational limitations and enable significant advancements in our understanding of the impact of jet-driven feedback on galaxy evolution.

2. Observing Jet-ISM feedback with the ngVLA

The most well-studied population of sources exhibiting radio jet-driven feedback consists of massive elliptical galaxies residing at the centers of galaxy clusters with powerful jets capable of influencing galaxy evolution through the regulation of cooling flows. Jet-ISM feedback may also occur on sub-galactic scales in lower-mass and/or gas-rich galaxies, which typically have less massive SMBHs and much weaker radio jets. However, the prevalence of low-power ($L_{1.4\,\mathrm{GHz}} < 10^{24}$ W Hz^{-1}), $\sim$kpc-scale radio jets, and their impact on galaxy evolution, remain poorly constrained. The ngVLA will be an ideal

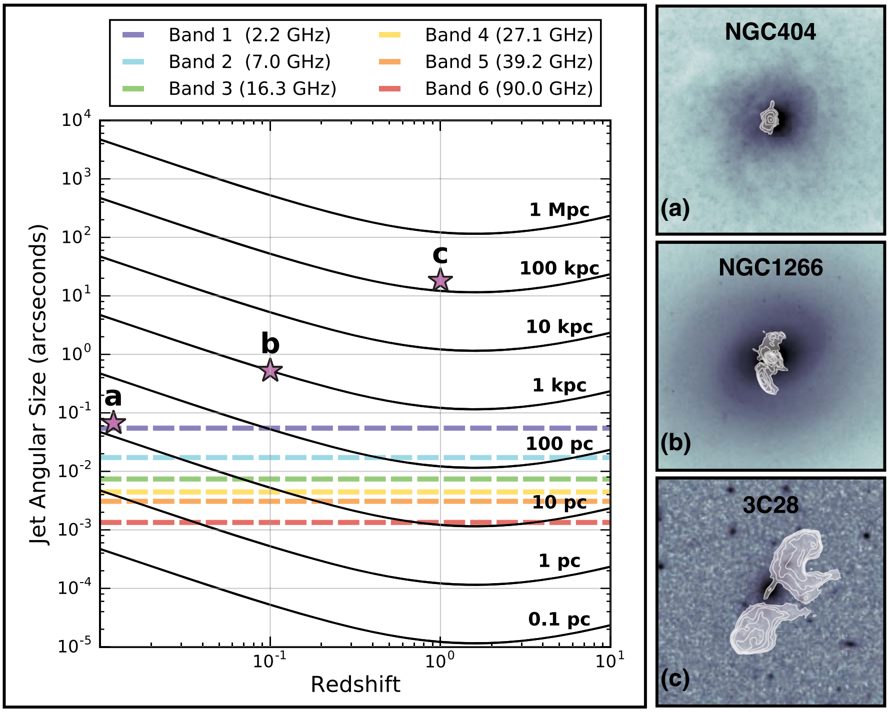

Figure 1. Jet angular size as a function of redshift. The black solid lines trace the redshift dependence of the angular extent of a jetted AGN for intrinsic jet sizes (measured from end to end along the major axis of the jet) from 0.1 pc to 1 Mpc. The maximum angular resolution of the ngVLA at the center of each of the ngVLA bands as defined in (Selina *et al.* 2017) is denoted by the dashed colored lines. The magenta stars and thumbnails to the right of the main figure indicate three jetted radio AGN representing a wide range of jet size scales: **a)** the dwarf galaxy NGC 404 with a jet extent of 10 pc, **b)** the jet-driven feedback host NGC 1266 with a jet extent of 1 kpc, and **c)** the radio galaxy 3C28 with a jet extent of 150 kpc. The redshifts of the representative sources correspond to simulated ngVLA maps from Nyland *et al.* (2018) at $z \approx 0$ ($D = 10$ Mpc), $z = 0.1$, and $z = 1.0$, respectively.

instrument for studying sub-galactic-scale radio jets and their impact on the interstellar medium (ISM), particularly for sources with extents of a few pc to a few kpc such as young radio AGN, jetted AGN hosted by low-mass galaxies, and radio jets that are interacting strongly with the interstellar medium of the host galaxy. Figure 1 illustrates the redshift dependence of the angular jet extent as observed by the ngVLA for a wide range of radio jet size scales ranging from sub-parsec jets to giant radio galaxies with Mpc-scale lobes. Thus, future ngVLA studies of radio jets with intrinsic extents of a few pc to a few kpc will be able to fully utilize the unique combination of angular resolution, collecting area, and frequency coverage of the ngVLA over a wide range of redshifts. *ISM Content and Conditions*. The ngVLA will link source morphologies and energetics from deep, high-resolution continuum observations with spectral line data that encode information on the ISM content and conditions. The combination of broadband continuum and spectral line imaging will allow the ngVLA to uniquely probe the energetic impact of radio jets on the cold gas reservoirs of their hosts. In particular, spectral line measurements of both the molecular (Figure 2) and atomic gas may be used to identify AGN-driven outflows, perform detailed kinematic studies to estimate the amount of energy injected into the ISM via feedback, and address the future evolutionary impact on the star formation efficiency on local/global scales caused by the AGN feedback (e.g.,

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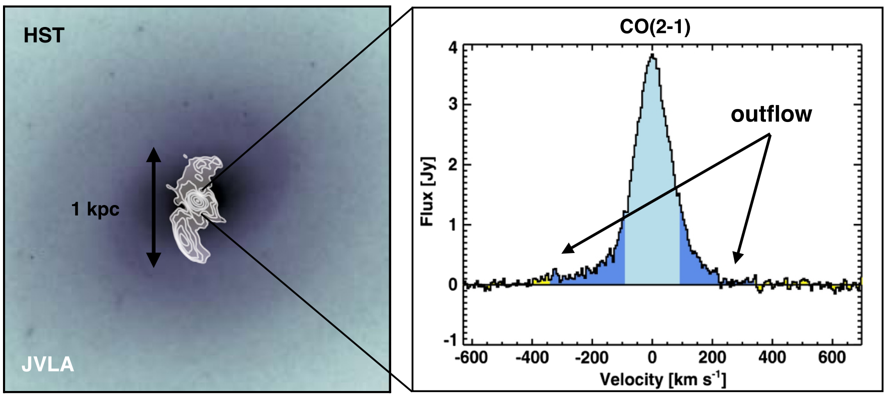

Figure 2. The radio jet and outflow of the nearby galaxy NGC 1266. **Left:** The background colorscale image illustrates the *HST* *J*-band data (WFC3, F140W; Nyland *et al.* 2013) and the filled white contours trace VLA 5 GHz continuum data from Nyland *et al.* (2016). **Right:** The CO(2–1) data from CARMA highlights the molecular outflow originally identified in Alatalo *et al.* (2011) based on the presence of excess emission in the wings of the spectrum (dark blue).

negative vs. positive feedback; Gaibler *et al.* 2012). Through comparisons with state-of-the-art jet-feedback simulations (e.g., Mukherjee *et al.* 2016), these continuum + cold gas ngVLA studies would place direct constraints on the prevalence and energetic importance of jet-ISM feedback as a function of redshift, galaxy mass, and environment.

Radio Spectral Ages. The ngVLA will uniquely excel at studies of radio AGN spanning a wide range of ages at low redshift, as well as radio AGN that are young or embedded in dense environments at higher redshifts (Figure 3). As shown by results from the Australia Telescope 20 GHz (AT20G) survey, continuum measurements in the tens of GHz range are needed to adequately model the radio spectral energy distributions (Sadler *et al.* 2006). This is particularly important for modeling the ages of young, low-redshift sources less than 10 Myrs old (Patil *et al.* 2018). Lower frequency continuum data in the MHz range will be important for constraining the ages of high-z sources; however, the inclusion of the lowest-frequency ngVLA bands down to ∼1 GHz would provide sufficient frequency coverage for measuring ages of sources as old as 30–40 Myrs at $z \sim 1$.

AGN Hosted by Low-mass Galaxies. Recent studies suggest that accreting SMBHs with masses in the range of $10^3 \lesssim M_{\rm BH} \lesssim 10^6$ $M_\odot$ may commonly reside in the nuclei of nearby low-mass ($M_* < 10^{10}\, M_\odot$) galaxies (Mezcua 2017, and references therein), thus motivating deep searches for their radio continuum signatures. However, identifying SMBHs in this population of galaxies is inherently difficult due to their faint accretion signatures. An ngVLA survey of accreting SMBHs hosted by nearby low-mass galaxies (e.g., analogs to NGC 404; Nyland *et al.* 2017) would offer new insights into the occupation fraction of SMBHs analogous to the SMBH seeds that formed at high redshift, thus profoundly impacting our understanding of the origin of SMBHs. Deep, high-angular-resolution observations with the ngVLA will both help constrain the SMBH seed mass distribution and also provide new constraints on the energetic impact of AGN feedback associated with sub-million-solar-mass SMBHs.

3. Opportunities for multiwavelength synergy

The unique capabilities of the ngVLA will facilitate exciting advancements in our understanding of AGN feedback and its broader connection to galaxy evolution, particularly when combined with multiwavelength data from other current and next-generation

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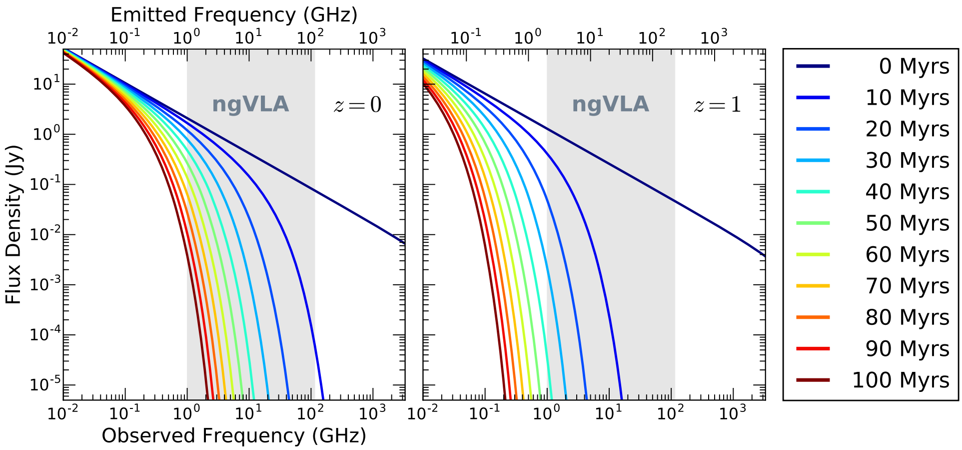

Figure 3. Example of JP model (Jaffe & Perola 1973) spectral ages calculated using the BRATS software (Harwood *et al.* 2013) demonstrating the need for ngVLA observations spanning a wide range of frequencies. The left and center panels correspond to redshifts of 0 and 1, respectively. The flux density values shown on the y-axis have been arbitrarily scaled. Because of its advantages of wide frequency range and angular resolution compared to the SKA, the ngVLA will uniquely excel in studies of low-redshift radio AGN that are young, or higher-redshift AGN that are embedded in dense environments.

instruments. In terms of synergy with current radio telescopes, observations with ALMA at frequencies above the ngVLA's limit of 116 GHz will provide key insights into the energetic and chemical impact of jet-driven feedback on the dense gas phase of the ISM. In the low radio frequency regime, the Square Kilometre Array (SKA) and its pathfinders will probe the 21 cm line out to higher redshifts (though at lower spatial resolution) than the ngVLA (Morganti 2017). The combination of constraints on both the atomic and molecular gas conditions from ngVLA and SKA observations will be important for studying the full impact of energetic jet-driven feedback on the ISM.

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