Astro2020 Science White Paper

AGN Feedback Driven by Jet-ISM Interactions on Sub-Galactic Scales: Opportunities for Advancement in the Next Decade

Thematic Areas: ☐ Planetary Systems ☐ Star and Planet Formation
☐ Formation and Evolution of Compact Objects ☐ Cosmology and Fundamental Physics
☐ Stars and Stellar Evolution ☐ Resolved Stellar Populations and their Environments
☑ Galaxy Evolution ☐ Multi-Messenger Astronomy and Astrophysics

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Abstract: As the most energetic, long-lived objects in the universe, active galactic nuclei (AGN) are capable of dramatically altering their surroundings through the process of AGN feedback. AGN feedback is believed to influence galaxy evolution through the regulation of star formation rates and efficiencies. The prevailing belief is that AGN feedback shapes galaxies through powerful quasar winds at high redshift and the regulation of cooling flows by classical radio galaxies at low redshift, and is thus limited in scope to the most luminous quasars and radio galaxies. However, recent evidence suggests that AGN feedback may operate under a much broader range of conditions. In particular, a key missing element in our understanding of radio jet-driven feedback and its importance to galaxy evolution is how it operates on (sub-)kpc scales in gas-rich galaxies, such as the hosts of "radio-quiet" quasars or Seyferts. In this white paper, we describe how the unique capabilities of the next-generation Very Large Array will enable new advancements in our understanding of the impact of radio jet-ISM feedback on galaxy growth and evolution.

1 Introduction

SMBH (super massive black-hole)-galaxy co-evolution is believed to operate via energetic feedback from active galactic nuclei (AGN), influencing galaxy evolution through the regulation of galaxy star formation rates and efficiencies. The conventional wisdom is that AGN feedback operates via two distinct modes: 1) the radiative or quasar mode, in which winds launched by the accretion disk quench star formation (SF) through the removal of a galaxy's star-forming reservoir, and 2) the jet or "maintenance" mode, in which large-scale ($\sim 10-1000$ kpc) jets influence SF through the inhibition of cooling flows in the intracluster medium. However, recent advancements have challenged this simple paradigm. Evidence continues to mount that lower-power ($L_{1.4\,\mathrm{GHz}} \lesssim 10^{24}$ W Hz^{-1}) jetted AGN may have a significant impact on their hosts through jet-ISM interactions on sub-galactic ($\sim 1-10$ kpc) scales that heat, expel, or shock the ambient ISM, thereby altering the star formation efficiency (e.g., [21, 2, 3, 13]). State-of-the-art simulations ([17, 18, 19]; Figure 1) provide further support, demonstrating that unlike powerful jets that rapidly "drill" through the ISM intact, lower-power jets are susceptible to disruption and entrainment, which increases the volume and timescale of the feedback, as well as the amount of energy transferred to the ISM.

Given that the majority of AGN ($\sim$ 90%; [25]) are characterized by low radio powers (i.e. radio-quiet AGN), these new results have exciting implications for our understanding of AGN feedback and SMBH-galaxy co-evolution. In this white paper, we highlight the new observational frontier of jet-ISM feedback on sub-galactic scales and prospects for scientific progress in the next decade. The most important open questions related to jet-ISM feedback on sub-galactic scales are:

- **What is the prevalence of compact, sub-galactic-scale radio jets across different cosmic epochs and in different galaxy populations?**
- **What is the dominant energy transfer mechanism between jets and the ambient ISM (e.g., outflows vs. shock-driven turbulence)?**
- **What is the relative importance of negative vs. positive feedback in jet-ISM interactions under different conditions, timescales, and cosmic epochs?**

2 Observational Requirements

Identifying jet-ISM iteractions on sub-galactic scales requires interferometric observations with a large collecting area, high angular resolution ($\theta_{\mathrm{FWHM}} \lesssim 0.1''$, which corresponds to $\lesssim$ kpc-scale resolution at $z \sim 2$), and broad frequency coverage (including receivers in both the cm and mm-wave regimes to capture synchrotron emission from jets and characterize the ISM content and conditions). These requirements pose challenges to current radio telescopes such as the VLA, ALMA, VLBA, and e-MERLIN, none of which has the necessary combination of sensitivity, resolution, and frequency coverage. A concept for a new radio telescope that is currently under development and would be well-suited for studies of kpc-scale jet-ISM feedback is the next-generation Very Large Array (ngVLA; [20]). In its current reference design, the ngVLA would operate from 1 to 116 GHz and provide up to 10X higher sensitivity and spatial resolution compared to the VLA. Given its unique capabilities, the ngVLA would serve as a transformational new tool in our understanding of how the dominant population of radio jets interact with their surroundings.

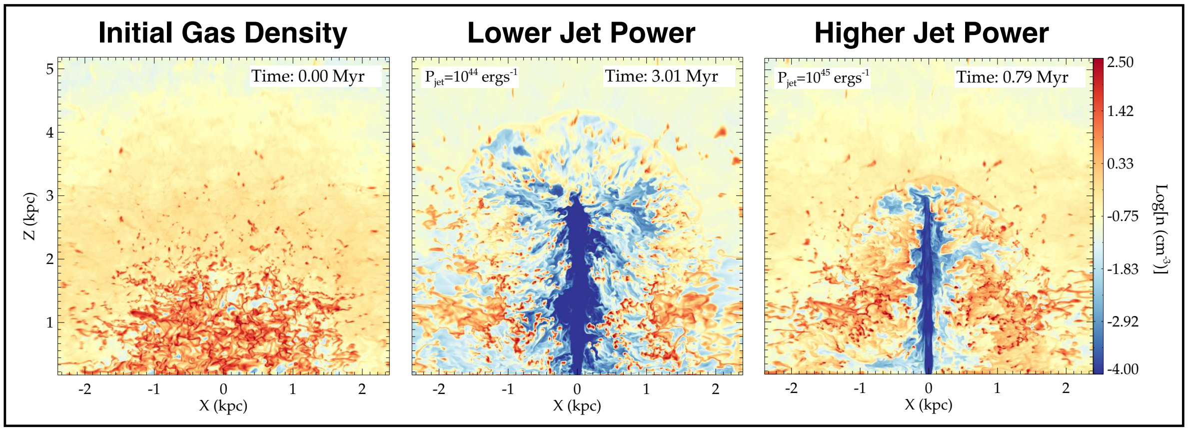

Figure 1: Snapshots from the relativistic hydrodynamic radio jet simulations [17, 18] showing the effect on an identical initial ISM (left) made by a radio jet with $P_{\text{jet}} = 10^{44}$ erg s^{-1} (center) and $P_{\text{jet}} = 10^{45}$ erg s^{-1} (right). The more powerful radio jet is able to more quickly "drill" through the ISM of its host galaxy, while the lower-power radio jet is trapped by the ISM and able to disrupt the surrounding gas for a longer time period and over a larger volume.

3 Advancements Enabled by the ngVLA

3.1 Prevalence of Compact Radio Jets

Compact radio sources associated with jetted AGN emission that is confined within the extent of the host galaxy may arise from two main mechanisms: 1) intrinsically low jet energy (as a result of intermittent or inefficient SMBH accretion, lower bulk jet velocities, low SMBH spin, entrainment with a dense ISM, or a combination of these factors), or 2) youth due to recently-triggered jet activity. Compared to the population of classical FRI/FRII [4] radio galaxies that have been studied extensively in the radio for nearly fifty years, compact radio AGN remain poorly understood. Of particular interest are young, compact radio AGN associated with luminous quasars in the redshift range of $1 \lesssim z \lesssim 3$ that have been traditionally considered "radio-quiet" ($L \lesssim 10^{24-25}$ W Hz^{-1}). These objects represent an important phase in the life cycles of jetted AGN for understanding AGN triggering and duty cycles [27]. However, all but the most luminous and/or most nearby young radio AGN are difficult to identify in low-resolution radio surveys such as NVSS and FIRST, and must await future wide-area radio surveys with next-generation instruments capable of providing sub-arcsecond spatial resolution, such as the ngVLA (Figure 2).

In addition, young radio AGN may be distinguished from other radio source populations based on their broadband radio spectral energy distributions (SEDs). The inclusion of the lowest-frequency ngVLA band down to ∼1 GHz would provide sufficient frequency coverage for measuring the ages of sources as old as $30 - 40$ Myrs at $z \sim 1$ [26]. The Next Generation LOw Band Observatory (ngLOBO; [28]), a proposed commensal enhancement to the basic ngVLA reference design, would extend the ngVLA's frequency range below 1 GHz. NgLOBO would enable significantly more robust radio SED and spectral aging model studies with the ngVLA, particularly for slightly older (> 10 Myr) and more distant ($z > 1$) sources (Figure 3). We therefore recommend the addition of a sub-GHz ngLOBO commensal capacity to the main ngVLA design.

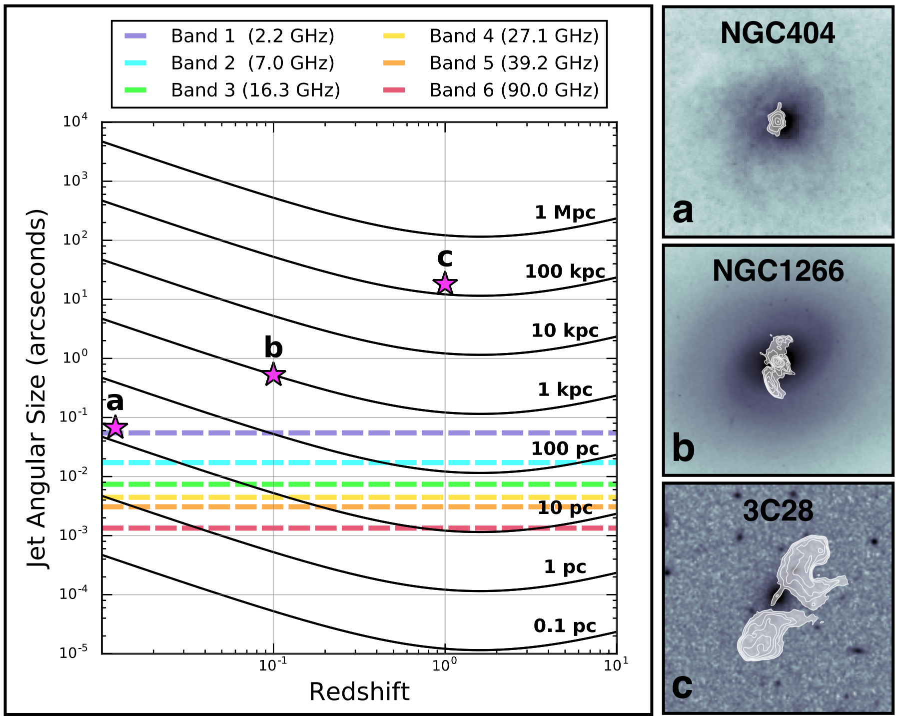

Figure 2: Jet size vs. redshift. The black solid lines trace the redshift dependence of the angular extent of a jetted AGN for intrinsic jet sizes from 0.1 pc to 1 Mpc. The angular resolution of the ngVLA at the center of each band as defined in [20] is shown by the dashed colored lines. The magenta stars and images on the right highlight 3 representative jetted AGN spanning a wide range of jet size scales. Adapted from [22].

3.2 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 ambient cold gas. Spectral line measurements of molecular and atomic gas on comparable angular scales (achievable through uv-tapering/inclusion of a short-baseline array in the ngVLA design) can be used to identify AGN-driven outflows (as well as gas inflow associated with fueling), perform detailed kinematic studies to gauge the amount of energy injected into the gas via feedback. Ultimately, cold gas and continuum estimates of the energetics of the outflow and jet can be directly compared with state-of-the art simulations, such as those shown in Figure 1, to deeply probe the underlying feedback physics.

3.2.1 Molecular Gas

The identification of molecular outflows (associated with jet-ISM feedback as well as radiative winds from quasar-mode AGN, starbursts, and supernovae) is crucial for improving our understanding of feedback. Molecular outflows may be identified on the basis of their spectral line shapes, such as the presence of broad wings [1]. In addition, more subtle feedback effects, such as a significant increase in the turbulence of the gas, or a substantial change in star formation efficiency/depletion time in the vicinity of the AGN, also provide important information on the energetics and underlying energy transfer mechanisms e.g. [2, 23]). Imaging the cold molecular gas in the vicinity of the AGN may also provide important clues on the fueling of the central SMBH. Depending on the geometry and kinematics of this gas (disks, patches, or filaments), the fueling mechanism and efficiency can be determined, in comparison with models (e.g. [9]). The low-J transitions of the CO molecule will fall within the ngVLA bands and are expected to be detectable over a wide range of redshifts. However, given the intrinsically low-excitation temperature of the

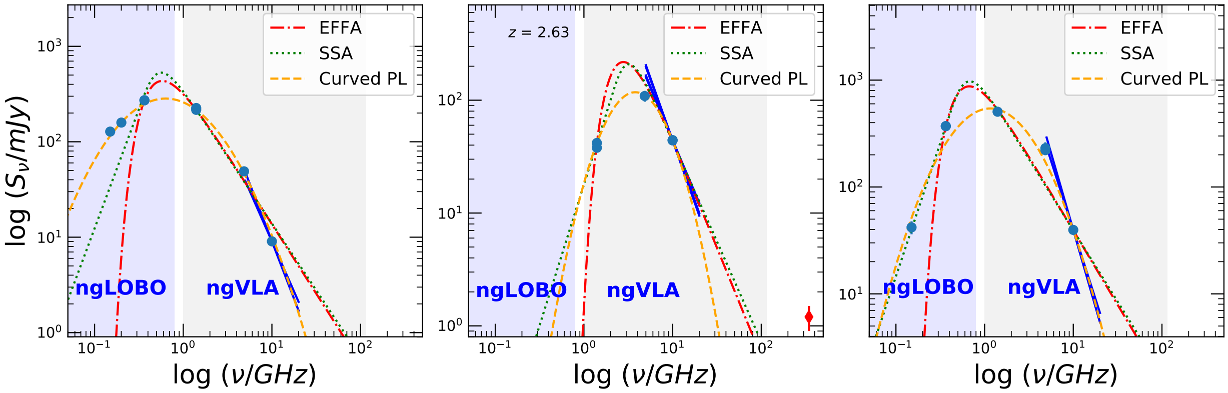

Figure 3: Example SEDs of young radio AGN. The curves show the best-fit solutions of different radio SED models. The gray and blue shaded regions denote the frequency ranges of the main ngVLA design and the addition of a commensal (i.e., to be operated in parallel with the main array) ngLOBO component, respectively. Further details are provided in [26].

low-J CO lines, we emphasize that the main reference design of the ngVLA will likely offer insufficient surface brightness temperature sensitivity, and we therefore encourage the inclusion of a short-baseline array in the final ngVLA design.

3.2.2 Atomic Gas

The absorption of atomic hydrogen at 21 cm against background continuum emission associated with a radio AGN probes the physical properties of ambient cold gas by characterizing the degree of turbulence [14] and directly constraining the kinetic energy of any outflow components (e.g. [21, 15]). H I absorption offers a key advantage over studies of the H I line in emission in terms of detectability, since the detection of H I absorption is independent of redshift and depends solely on the underlying strength of the background continuum source. In the context of jet-driven feedback, the detection of a blue-shifted spectral component in H I absorption is a strong signature of an outflow, which can be unambiguously distinguished from other possibilities, such as inflow or rotation. The ability of the ngVLA to observe the H I line will depend on the lower frequency cutoff of its observing range. With the current lower limit of 1.2 GHz, ngVLA H I studies would be limited to nearby galaxies ($0 < z < 0.1$). Extending the ngVLA's frequency range below 1 GHz with a commensal low-band system (ngLOBO; [28]) would greatly expand the redshift range over which high-resolution H I absorption studies would be possible with the ngVLA.

3.3 Polarimetry

Broadband polarimetric measurements of the degree of Faraday rotation probe the line of sight combination of magnetic fields and ionized gas towards radio-emitting plasma. Faraday effects can arise from properties intrinsic to the jet, external screens of magnetized plasma between the observer and the jet, or entrained ISM mixed with the jet material. ([10], and references therein). Each of these effects have different, wavelength-dependent signatures, but distinguishing between them requires high sensitivity for the detection of inherently faint polarization signatures, high angular resolution for measuring spatial gradients in the rotation measure (RM), and broadband observing capabilities from cm to mm wavelengths.

The observing capabilities of the ngVLA make it an ideal tool for probing magnetic fields, jet formation, and feedback in radio AGN through their polarimetric properties. The ngVLA would be well-equipped for observations of extreme RMs ($\gtrsim 10^4$ rad m^{-2}) at mm wavelengths that are typically depolarized in the cm-wave regime, such as 3C273 [11]. In addition to linear polarization (Stokes Q and U) studies, the high sensitivity of the ngVLA will also enable circular polarization (Stokes V) measurements, which will constrain the jet composition and the amount of material entrained by the jet [24, 12, 29].

3.4 Positive and Negative Feedback

Jet-driven feedback is typically assumed to be *negative* in nature in that it involves the destruction, disruption, and/or removal of gas that might otherwise be engaged in star formation. However, *positive* radio AGN feedback – in which radio jets actually trigger the onset of star formation or lead to an increased star formation efficiency – may also occur. Simulations have shown that the relative importance of negative and positive jet-driven feedback depends on both ISM properties and the strength of the shocks induced by the radio jets [6, 7, 8, 5] Recently, [14] directly observed the effects of positive feedback in Minkowski's Object, a rare local example of jet-triggered SF, by combining deep VLA continuum and H I observations with ALMA CO data. While the VLA and ALMA are capable of performing additional detailed case studies of positive jet-driven feedback, sensitivity limitations, particularly for spectral line observations, would pose serious challenges to systematic searches for Minkowski's Object analogs at higher redshifts. A significant advancement in our understanding of the roles of positive and negative AGN feedback in the scheme of SMBH-galaxy co-evolution and as a function of redshift and other galaxy properties will require the high sensitivity of the ngVLA.

4 Multiwavelength Synergy in the Next Decade

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 state-of-the-art instruments. In terms of 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. At lower frequencies, the SKA and its pathfinders will probe the 21cm line out to higher redshifts (though at lower spatial resolution) than the ngVLA [16], thus probing the full impact of jet-driven feedback on cold gas.

Beyond the radio regime, sensitive, high-resolution observations in the infrared, optical, and X-ray will naturally complement the observing capabilities of the ngVLA. In particular, new 30-meter-class optical telescopes, the *JWST*, and the proposed X-ray NASA flagship mission *Lynx*, would probe the conditions and kinematics in different phases of the ISM. For outflows or jet-driven turbulence, multi-phase constraints will be essential for modeling the complex energetics and chemistry associated with jet-ISM feedback.

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