Precision Gas-dynamical Mass Measurement of Supermassive Black Holes with the ngVLA

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Abstract. Emission line observations of circumnuclear gas disks in the ALMA era have begun to resolve molecular gas tracer kinematics near supermassive black holes (BHs), enabling highly precise mass determination in the best cases. The ngVLA is capable of extremely high spatial resolution imaging of the CO(1−0) transition at 115 GHz for nearby galaxies. Furthermore, its high (anticipated) emission line sensitivity suggests this array can produce benchmark BH mass measurements. We discuss lessons learned from gas-dynamical modeling of recent ALMA data sets and also compare ALMA and ngVLA CO simulations of a dynamically cold disk. While only a fraction of all local galaxies likely possess sufficiently bright, regularly-rotating nuclear molecular gas, in such cases the ngVLA is expected to more efficiently resolve such emission arising at a projected 50−100 mas from the central BH.

1. Introduction

The observed properties of massive, bulge-dominated galaxies support the existence of a strong co-evolution between the formation and growth of their stellar spheroids and the supermassive black holes (BHs) residing in their nuclei (e.g., Kormendy \& Ho 2013; Heckman \& Best 2014). Accurate BH mass measurements are necessary to investigate BH growth over cosmic time as well as to improve constraints on theoretical models of their formation at high redshift. Despite the importance of these measurements to our understanding of galaxy evolution, the full distribution of BH masses at fixed galaxy properties such as morphology, redshift, and stellar mass – particularly for lower-mass central BHs – remains poorly constrained (e.g., Greene et al. 2016). ALMA is now beginning to have its long-anticipated (e.g., Maiolino 2008) revolutionary impact on circumnuclear kinematic studies, already facilitating precision BH mass measurements (e.g., Barth et al. 2016a; Davis et al. 2017) using more common molecular gas tracers. In this science case, we first describe the benefits and challenges associated with cold molecular gas emission as a kinematic tracer, and afterwards detail the promise of
2. Measuring BH masses with Molecular Gas Tracers

Gas-dynamical modeling of a thin coplanar disk within a galaxy nucleus is an appealing technique to determine its central BH mass ($M_{BH}$). In addition to conceptual and computational simplicity, idealized rotating disks are also free from most of the potentially serious systematics that affect stellar-dynamical $M_{BH}$ measurements (e.g., van den Bosch & de Zeeuw 2010; McConnell et al. 2013) and can be applied to systems with larger-scale stellar non-axisymmetries (such as bars and mergers). Many early
studies used observations of ionized atomic gas disks to map the gravitational potentials of galaxy nuclei, but modeling complications (especially gas turbulence; see van der Marel & van den Bosch 1998; Walsh et al. 2010) limit the confidence of $M_{\text{BH}}$ determinations from such kinematically warm tracers (Kormendy & Ho 2013). Dynamically cold molecular emission is a promising avenue as such relaxed systems retain the benefits of disk-like rotation while avoiding the primary systematics afflicting the treatment of ionized gas disks. In most cases, these dynamically cold disks are found to be nearly ideal central probes of nearby galaxies. The centers of many late and early-type galaxies (LTGs/ETGs), possessing both active and quiescent nuclei, contain significant molecular gas reservoirs ($\gtrsim 10^7 \, M_\odot$; Bolatto et al. 2017; Alatalo et al. 2013), indicating that BH masses in nearly all types of galaxies may be measured in the same manner by observing and modeling cold molecular gas rotation.

Unambiguously detecting a BH’s kinematic impact hinges on (at least approximately) resolving its sphere of influence $r_g \approx GM_{\text{BH}}/\sigma^2$ wherein $M_{\text{BH}}$ dominates over the extended mass contributions and gives rise to an elevated stellar velocity dispersion $\sigma_\star$. Even moderate (0.3″ – 0.5″) resolution, sensitive molecular line observations with ALMA have the potential to provide dynamical BH mass measurements (or strong constraints) for perhaps several hundred nearby ($\lesssim 100$ Mpc) galaxies (Davis 2014), thereby greatly increasing the number of $M_{\text{BH}}$ determinations made through dynamical means. Precision BH mass measurements (at the few percent level or better) require resolving kinematic tracers well within $r_g$, where the observed rotation is maximally sensitive to the BH influence. In the best (but rare) examples, extremely well-resolved extragalactic H$_2$O megamaser disks trace out clear Keplerian rotation and yield “gold standard” $M_{\text{BH}}$ values (generally $\sim 10^7 \, M_\odot$) for these active galaxies (e.g., Miyoshi et al. 1995; Kuo et al. 2011).

Disentangling the central rapid gas velocities of more common molecular tracers such as CO has been largely unachievable by the previous generation of mm/sub-mm arrays due to beam smearing: for example, a $10^8 \, M_\odot$ BH will have a projected $r_g \sim 0.2″$ when viewed at a distance of 20 Mpc. For one such nearby galaxy, Davis et al. (2013) used the CARMA array to just barely resolve CO(2–1) emission originating within the sphere of influence and permit the first BH mass constraint using CO kinematics. Now, ALMA facilitates much deeper, higher angular resolution imaging of this and other tracers in a fraction of the time. Data sets that just marginally resolve $r_g$ have already produced gas-dynamical BH mass measurements with total uncertainties (on the order of 20 – 30%, including systematics; Barth et al. 2016b; Onishi et al. 2017; Davis et al. 2017, 2018) that are commensurate with those derived from stellar-dynamical modeling. Observations that more fully resolve $r_g$ can produce benchmark $M_{\text{BH}}$, enabling tests on the assumptions used in other techniques when applied to measure the same BH mass (e.g., Barth et al. 2016a; Rusli et al. 2011).

3. Lessons From ALMA Observations

Over an order of magnitude higher maximum angular resolution imaging at $\sim 115$ GHz than ALMA initially suggests that the ngVLA will make possible correspondingly more precise BH mass measurements. This array is theoretically capable of resolving the spheres of influence for a Milky Way-analog BH observed at $\sim 100$ Mpc, as well as for $\sim 40\%$ of the galaxies in SDSS. However, not all nearby galaxies possess bright circumnuclear molecular gas emission originating from within $r_g$. Among those that do,
some fraction will exhibit relaxed central gas kinematics. Given the relatively smaller angular $r_g$ sizes of LTGs, kinematic studies that resolve $r_g$ for these targets are still nascent. We here focus on ETGs as they provide a clearer illustration. Roughly half of all luminous E/S0 hosts harbor detectable CO emission, although perhaps in only $\sim 10\%$ does the gas exhibit dynamically cold rotation (Alatalo et al. 2013). Recent ALMA observations reveal that commonly utilized molecular species tend to be dissociated (or are at least underluminous) in the central 10-100 pc (Onishi et al. 2017; Barth et al. 2016a; Boizelle et al. 2017; Davis et al. 2018).

Boizelle et al. (2017) estimate that perhaps a few percent of all ETGs will be prime candidates for precision BH mass measurement using ALMA. A handful of these (and some unknown fraction of LTGs) may still show strong, unresolved Keplerian-like rotation at the edge of ALMA capabilities, warranting even higher angular resolution line imaging with the ngVLA. Obtaining such well-resolved observations, with several independent resolution elements across $r_g$, alleviates nearly all of the remaining degeneracies (e.g., between $M_{BH}$ and the gas turbulent velocity dispersion; Barth et al. 2016a,b) and systematics (e.g., uncertainty in the extended mass velocity profile due to central dust obscuration; Barth et al. 2016b, Boizelle et al. 2018, in prep.). We believe this proposed cm/mm array will be optimally utilized when following up on previous interferometric observations (with $\theta_{1/2} \lesssim 0.25''$) that clearly identify gas emission within $r_g$. Its anticipated sensitivity will also aid in detecting faint central emission that is otherwise beneath the limit of previous ALMA observations.

4. ngVLA Unique Capabilities

High-resolution observations of the CO(1−0) transition (with line excitation temperature $T_{ex} \sim 5 – 10$ K) using ALMA are limited by extended configuration overheads and brightness temperature sensitivities. Typical CO surface brightness measurements suggest that ALMA is capable of resolving CO(1−0) emission interior to (with about four independent resolution elements across) $r_g$ for nearby galaxies with large projected spheres of influence ($\sim 0.2'' – 0.3''$; e.g., Boizelle et al. 2017; Davis et al. 2017, 2018). An integrated line S/N $\gtrsim 10$ ensures confident detection of kinematic features in these disks with low intrinsic line widths ($\sigma \sim 5 – 20$ km s$^{-1}$; see Barth et al. 2016a). Achieving this S/N level requires rms sensitivities $\sim 0.2 – 0.4$ mJy/beam in 10 km s$^{-1}$ channels, with the resulting ALMA 115 GHz on-source (total) integrations times ranging between 3–14 (9–32) hours. As a result of these requirements, kinematic studies of local galaxies with ALMA often focus on the 2–1 transition to better balance limiting sensitivities, weather constraints, and achievable angular resolution. Based on current performance metrics, ngVLA CO(1−0) observations with the same channel spacing are expected to reach of order $\sim 100$ microJy/beam line rms (producing S/N $\sim 20$ in a single hour (on-source) on 100 mas scales. These expected results also improve on ALMA Band 6 forecasts, more than halving the time allocation to accurately measure CO line properties at $\sim 0.1''$ resolution.

In Figure 1, we show our simulated ALMA and ngVLA full-cube CO(1−0) observations of a model molecular disk to compare array capabilities. The combination of higher angular resolution and lower limiting sensitivities enable detection of additional faint, high-velocity central emission that promotes a more confident $M_{BH}$ determination. Slightly higher angular resolution ngVLA imaging of such circumnuclear disks should be possible on 50 mas scales for reasonable (a few hours) integration times. On
Figure 2. Minimum BH mass detectable using the ngVLA at $\sim 115$ GHz (with a uv taper to achieve 50 mas angular resolution) as a function of luminosity distance assuming a standard cosmology (Planck Collaboration et al. 2016). Data points represent the elliptical and classical bulge galaxies on which the $M_{\text{BH}} - \sigma_*$ relation is currently based (Kormendy & Ho 2013). Curves show the mass limit reachable by the ngVLA using CO(1−0) observations that just marginally resolve the BH sphere of influence (dashed; as is typical for most stellar/gaseous $M_{\text{BH}}$ determinations) and that more highly resolve $r_g$ (solid); assuming detectable CO emission in regular rotation within $r_g$, expected total mass uncertainties are about 20 − 30% and $\lesssim 10\%$, respectively.

these angular scales, moderately accurate ($\sim 20\%$) $M_{\text{BH}}$ determinations of $\sim 10^9 M_\odot$ should be possible for galaxies at distances of up to 300 Mpc, with precision ($\lesssim 10\%$) measurements to nearly 75 Mpc (see Figure 2). Almost two orders of magnitude higher resolution CO(1−0) observations are technically feasible with this cm/mm array. However, the typical CO emission deficit at radii deep within $r_g$ and prohibitively long integration times suggest that ngVLA extreme angular resolution observations are not likely to be very useful for BH studies in most cases.

The above scenario focused on galaxies with large angular $r_g$ sizes, tending to favor nearby ETGs. The anticipated array performance suggests that ngVLA CO imaging is likely able to identify lower mass ($\sim 10^7 M_\odot$) BH kinematic signatures in late-type targets out to at least 20 Mpc. High-resolution cold molecular gas observations of such (often dusty) nuclei will result in more confident mass determinations than typically obtained using ionized atomic tracers (Beifiori et al. 2009) as well as better constraints on the low-mass end of the BH/host galaxy scaling relationships. This proposed array is also likely to be impactful in extragalactic H$_2$O megamaser BH mass measurements in active galaxies that provide direct geometrical measurement of $H_0$ (see Braatz et al. 2018, this work). While its longest baselines are not able to map out the 22 GHz
emission at sub-mas resolution, ngVLA will provide an important large-collecting area element in new and revised VLBI campaigns at greater sensitivity.

5. Multiwavelength Synergy

The next generation of giant segmented mirror telescopes (such as the E-ELT and the TMT) will offer angular resolutions down to mas scales, comparable to those technically achievable using the ngVLA in its high-frequency bands. These optical/NIR observatories will dramatically increase the number of unobscured nuclei for which it is possible to directly probe stellar and gaseous kinematics within the BH sphere of influence. Space-based NIR observations with the James Webb Space Telescope are expected to expand the sample of active galaxies with quality \( M_{\text{BH}} \) values using techniques such as reverberation mapping. Ongoing ALMA work is now providing tight BH mass constraints for galaxies with obscured nuclei, and the ngVLA contributions are expected to increase both the precision and number of these dynamical measurements. These highly complimentary avenues promise to more fully fill in the BH census with high-quality measurements spanning BH mass and host galaxy properties. Increasing the number of candidates for detailed dynamical modeling will similarly increase the number of cases where multiple techniques are applicable to the same target. Such precision \( M_{\text{BH}} \) values will enable crucial studies of the underlying assumptions and systematics inherent to each method.

6. Summary

The ngVLA will expand on ALMA’s revolutionary capability to probe cold molecular gas rotation within BH \( r_g \). Anticipated factor of at least \( \sim 2 - 4 \) improvements in line sensitivity with the ngVLA should enable detection of additional faint circumnuclear CO(1−0) emission, and an estimated maximum angular resolution of about 50 mas will better resolve Keplerian rotation for galaxies out to a greater distance. The ngVLA is therefore expected to drive the field of BH mass measurement towards more highly resolving cold gas kinematics that in turn facilitate more precise \( M_{\text{BH}} \) determinations.

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