ngVLA Memo No. 39: Thoughts on transient discovery

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Abstract: This report summarizes some of the outcomes of the ngVLA community study "Centimeter-wavelength Observations of Cosmic Cataclysms". It was quickly decided to focus this study on the potential for the ngVLA to discover counterparts to exotic events of unknown origin, wherein the ngVLA would be able to accurately localize them, and determine various physical characteristics. Here I consider the specific example of the coalescences of binary supermassive black holes to be detected in gravitational waves by the Laser Interferometer Space Antenna (LISA). I also discuss possible interloper sources and how they may be identified. Finally, I provide some general technical considerations for the problem of finding a specific transient/variable radio source in up to few deg^2 regions on the sky.

1. Introduction

Centimeter-wavelength observations of extragalactic cataclysms and outbursts have resulted in some of the most exciting discoveries in time-domain astronomy. Most recently, the VLA-discovered radio afterglow of the first binary neutron-star merger event to be detected in gravitational waves (GWs; Abbott et al. 2017) has proven decisive in determining the geometry, energetics and composition of the pre- and post-event ejecta (Alexander et al. 2017; Hallinan et al. 2017; Mooley et al. 2018). The VLA also provided the first interferometric localization of a Fast Radio Burst (FRB), conclusively establishing the distant-extragalactic nature of the phenomenon and identifying an FRB host galaxy (Chatterjee et al. 2017). Observations of evolving radio emission associated with the tidal-disruption and accretion of stars by supermassive black holes (tidal disruption events; TDEs) have revealed a diversity of outcomes, from sub-relativistic outflows (Alexander et al. 2016) to relativistic jets (e.g., Zauderer et al. 2011). Radio monitoring of the afterglows of γ-ray bursts (GRBs; Frail et al. 2001) and giant flares from soft gamma repeaters (Frail et al. 1999) have enabled accurate calorimetry of the explosions, and the characterization of beaming in GRBs. In turn, the presence or absence of rapidly evolving radio emission has proven to be a crucial discriminant between stellar explosions that result in transient relativistic jets, and those that do not (e.g., Soderberg et al. 2006). Finally, monitoring of the multi-frequency lightcurves of several tens of nearby supernovae (Weiler et al. 2002) have characterized the circum-explosion environments and outflow energetics, revealing for example pre-explosion mass loss episodes in core-collapse events. VLBI multi-epoch imaging, together with Australia Telescope Compact Array imaging of SN1987A in the Large Magellanic Cloud, has directly followed the expansion of supernova remnants into the surrounding medium (Bartel et al. 2017).

This report is focused on the prospects for the ngVLA discovery and characterization of radio emission from enigmatic extragalactic cataclysms and outbursts. I constrain the scope of the report in the following ways.

A focus on discovery. In considering and analyzing scientific use-cases for the ngVLA, care must be taken to ensure that they will remain relevant in the ngVLA era. For example, although radio emission from TDEs is a rare phenomenon at present, TDE candidates themselves are currently few and far between. The expected proliferation of several thousand optical- and X-ray detected TDEs in the coming decade by the Large Synoptic Survey Telescope (LSST; LSST Science Book, Chap. 8) and the eROSITA instruments will transform the field, making it difficult to assess the substantive likely contributions of the ngVLA to further our understanding of the TDE phenomenon. Below, I discuss the potential of the ngVLA to localize and characterize electromagnetic emission from the mergers of supermassive black holes (SMBHs) to be detected in GWs by the Laser Interferometer Space Antenna (LISA; Amaro-Seoane et al. 2017) and its potential companion missions (Luo et al. 2016; Hu & Wu 2017). These facilities are expected to be constructed on a similar timescale to the ngVLA.

Variable and transient radio emission on timescales $\gtrsim$days. Transient and variable radio emission from astrophysical sources has been detected on timescales of nanoseconds to decades. Here I limit the discussion to sources that vary on timescales greater than several hours. This naturally includes both coherent and incoherent-synchrotron sources of radio emission.

Uncertain a priori localizations. This report specifically concerns ngVLA observations of transient events first detected by other observatories, as opposed to independent ngVLA searches. In some cases, such as optical- or infrared-detected events, the initial localizations will be within an order of magnitude of the synthesized beamwidth of the ngVLA. However, in other cases (high-energy, particle, or GW events), larger areas would need to be searched by the ngVLA. I focus on the latter case here, wherein the ngVLA will be critical to the discovery, accurate localization, and characterization of the events.

In the following, I begin with a description of a specific ngVLA scientific program regarding the localization and characterization of binary-SMBH coalescence events (§2). I then present a characterization of the population of astrophysical transient and variable interlopers that will impact the proposed observations (§3). I conclude with a summary of the technical requirements for this ngVLA use case (§4).

2. Event discovery with the ngVLA: LISA sources

Following the success of the LISA Pathfinder mission (Armano et al. 2016), the European Space Agency selected a three-satellite LISA mission for its L3 launch in 2034. Central to the LISA science case is its potential for the study of SMBHs (black holes central to each galaxy, with masses $> 10^6 M_\odot$) coalescing at the centers of galaxy merger remnants. LISA will detect GWs from a few to a few$\times 10^2$ coalescing binary SMBHs each year. LISA detections of inspiralling and coalescing binary SMBHs will probe the wholly unknown formation and growth mechanisms of SMBH seeds, and help unravel the rich astrophysics that governs the fates of binary SMBHs in merging galaxies (for reviews, see Haiman 2013; Colpi 2014).

Much of the uncertainty in population synthesis models for the binary SMBHs to be detected by LISA reflects our lack of knowledge of the formation and evolution of these systems (Klein et al. 2016). For example, the two leading models for SMBH seeding result in detection rates that vary by an order of magnitude for some LISA configurations. The characteristics of the $10^{-4} - 0.1$ Hz LISA sensitivity curve, combined with the nature of GW emission from binary systems, makes LISA most sensitive to the coalescences of binaries with masses $M_B \sim 10^5 - 10^8 M_\odot$ at redshifts up to $z \sim 10$. GWs from binary SMBHs will sweep through the LISA frequency band for days to years, and localization error regions of $\sim 1 - 10\,\mathrm{deg}^2$ are expected in the days to weeks prior to coalescence (Lang & Hughes 2008).

Electromagnetic (EM) identifications of LISA-detected binaries are required to realize their scientific promise. GW-only detections of SMBH-SMBH coalescence events will supply component masses and redshifts with $O(10\%)$ accuracies (Hughes 2002). However, redshifts based on host-galaxy identifications will fully specify the parameters of the coalescing systems, and enable their use as alternative probes of cosmological expansion (Tamanini et al. 2016). The characterization of coalescing-SMBH host galaxies will also provide clues to the environments and mechanisms conducive to the formation and orbital decay of binary SMBHs (Colpi 2014). The nature of the EM signature itself will further test models for interactions between the SMBHs and their environments, such as the formation and sustenance of accretion disks and relativistic jets (Schnittman 2011). The ngVLA can discover the radio counterparts to binary SMBHs caught in the act of coalescence by LISA. Below I describe the essential characteristics of the radio-counterpart model; a detailed account will be given elsewhere.

Binary SMBHs will likely form in environments rich in dynamically cold gas (Kelley et al. 2017), and thus be embedded in accretion disks. Several groups have simulated the evolution of fossil accretion disks around that SMBHs inspiral and coalesce due to the loss of energy and angular momentum to GW emission. The most recent work hass been conducted by Giacomazzo et al. (2012) and Kelly et al. (2017). Immediately upon SMBH-SMBH coalescence, the simulations predict a transient (few-hour) collimated Poynting-flux outflow along angular-momentum vector of the binary, with a luminosity of $L_{\mathrm{prompt}} = 5 \times 10^{47}[M/(10^8 M_\odot)]^2\,\mathrm{erg\,s^{-1}}$ (where M is the initial SMBH mass, assuming an equal mass-ratio system). Eventually, on a timescale of $\tau_{\mathrm{final}} \sim 10^6[M/(10^8 M_\odot)]$ s after coalescence, the system settles into a steady collimated Poynting-flux outflow, with a somewhat larger luminosity of $L_{\mathrm{final}} = 10^{48}[M/(10^8 M_\odot)]^2$ $\mathrm{erg\,s^{-1}}$. Note that all quantities are quoted for fiducial values of the accretion-flow magnetic-energy and particle density, although they are robust to reasonable variations in these parameters. Collimated Poynting-flux outflows are the leading model for the launching of relativistic astrophysical jets (e.g., Spruit 2011). Based on VLBI observations of superluminal AGN jets, I adopt a jet Lorentz factor of $\Gamma_0 = (1 - \beta^2)^{-1/2} = 10$, and assume that particle entrainment occurs on sub-parsec scales. Further assuming full efficiency in the conversion of Poynting flux to jetted matter/energy, I model the Poynting-luminosity increase coincident with SMBH-SMBH coalescence as a $\tau_{\mathrm{prompt}} = 10^3[M/(10^8 M_\odot)]$ s transient jet with a total energy output of $E_{\mathrm{prompt}} = 5 \times 10^{50}[M/(10^8 M_\odot)]^3$ erg. The properties of the final jet (τ_{final} and L_{final}) are as above.

Radio emission due to relativistic jets and outflows is generated by electrons emitting synchrotron radiation. For on-axis AGN (e.g., blazars, BL Lacs), a correlation exists between the bolometric luminosity $L_{\rm jet}$ (for which the γ-ray luminosity is a rough proxy) and the radio-synchrotron luminosity $L_{\rm rad} \sim \nu L_\nu$, where ν is the radio frequency and L_ν is the radio spectral luminosity at its approximate peak (Ghirlanda et al. 2011). The bolometric luminosity can in turn be estimated using the total jet kinetic power $P_{\rm jet}$ (Nemmen et al. 2012). These empirical results suggest peak radio flux density of the persistent final jet associated with a binary-SMBH coalescence event of

$$F_{\rm final} \approx 15a^3[M/(10^8 M_\odot)]^2[D_L/(45\,{\rm Gpc})]^{-2}\,{\rm mJy}, \tag{1}$$

where $a = (1-\beta)/(1-\beta\cos\theta)$ ($\beta = (1-\Gamma^{-2})^{-1/2}$) is a factor that accounts for an off-axis observer orientation at an angle θ, D_L is the luminosity distance, and I assume $\nu_p = 10\,{\rm GHz}$ for the rest-frame spectral peak.[1] Equation 1, and the assumption of a constant-Γ jet, implies that the final jet is only important for small viewing angles θ. For example, $\theta = 60^\circ$ implies $a = 0.01$, reducing the fiducial $F_{\rm final}$ to 15 nJy. Note that the GW strain amplitudes emitted by face-on binaries are a factor of four larger than those emitted by edge-on binaries, and that small values of θ are therefore more likely to be observed.

The $L_{\rm jet} - L_{\rm rad}$ correlation, which is stronger when only variable emission is considered (albeit with a time-lag), is interpreted as all the EM emission originating from particles accelerated in internal shocks within jets. In the case of newly launched transient jets such as in GRBs, particle acceleration also occurs in the external shock at the interface between the jet and the circum-nuclear medium (CNM). The initial transient jet will drive a relativistic shock through the CNM, which becomes Newtonian once the kinetic energy of the swept-up CNM is equivalent to that of the jet. The final jet will in turn power a shock within the initial jet, with the radio luminosity estimated above, that will further accelerate the forward CNM shock when it catches up with it.

I model the radio emission associated with the external CNM shock using the semi-analytic calculations of (Leventis et al. 2012) implemented in their *Spherefit* code. Although these results were derived for a spherical outflow, they are equally applicable to an on-axis observer of a relativistic jet. To evaluate the off-axis emission, I apply straightforward relativistic corrections relevant to a point-mass in linear motion, and ignore any contributions to the observed radio emission from a reverse shock propagating backwards through the transient jet. Observations of stellar tidal disruption events (e.g., Alexander et al. 2016) motivate the fiducial CNM number-density profile of $\rho(r) = 10[r/(10^{17}\,{\rm cm})]^{-1.5}\,{\rm cm}^{-3}$. Predicted lightcurves for the external-shock emission are shown in Fig. 1.

Emission in EM bands besides the radio is unlikely to be of significant importance for the jet model considered here, unless the jet is viewed on-axis. Synchrotron emission from the CNM shock will be most readily detected in the radio band (Sari et al. 1998). Relativistic jets powered by SMBHs are also most easily detected in the radio band at high redshifts (e.g., Miley & De Breuck 2008). However, the wider landscape of (non-jetted) EM signatures of SMBH-SMBH coalescence is a topic of intense investigation. On prompt timescales, for example, the near-field perturbations of space

[1]Compact radio sources with spectral peaks in the tens of GHz range are thought to be the youngest instances of active galaxies (O'Dea 1998). This motivates the fiducial choice of $\nu_p = 10\,{\rm GHz}$ for the spectral peak of the persistent final jet.

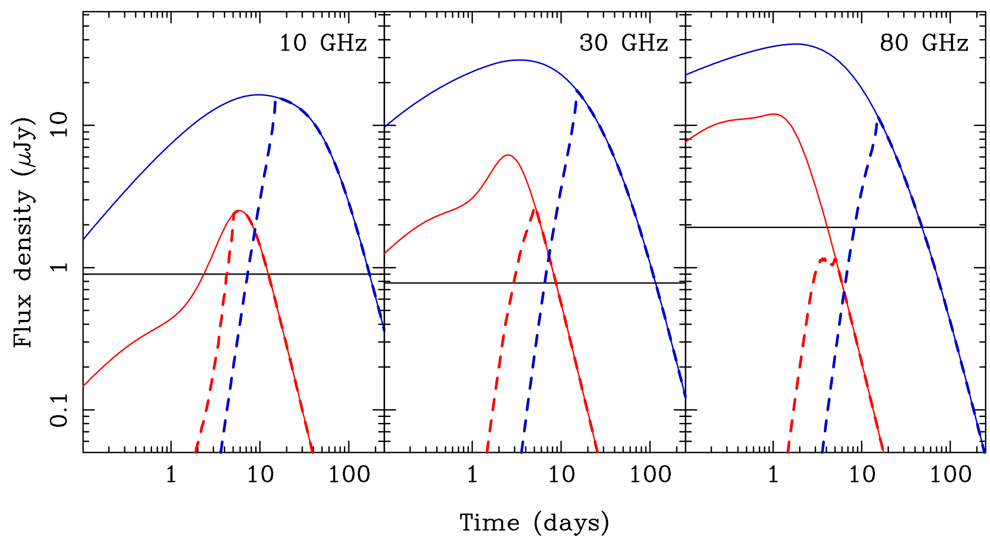

Figure 1. Predicted lightcurves at 10 GHz, 30 GHz and 90 GHz of emission corresponding to the external CNM shock due to the prompt transient jet predicted to occur during SMBH-SMBH coalescence events. The blue (higher-flux) curves correspond to the merger of two $10^8 M_{\odot}$ SMBHs at $z = 5$, and the red (lower-flux) curves correspond to the merger of two $10^7 M_{\odot}$ SMBHs at $z = 1$. The solid curves were calculated for on-axis observers, while the dashed curves were calculated for a viewing angle of $60^{\odot}$ to the jet direction. The horizontal dashed lines are the 6σ detection thresholds for 9 h ngVLA observations in each band (ngVLA Memo #5).

caused by the coalescing SMBH will partially dissipate into any gas present, resulting in a tens-of-minutes thermal EM flare that can be comparable to the Eddington luminosity of the system (Krolik 2010). Rapidly time-variable emission may also be caused by the gravitational recoil of the post-coalescence SMBH perturbing the accretion disk (Anderson et al. 2010).

3. Transient and variable interlopers

The ngVLA will need to conduct multi-epoch surveys of GW localization regions of several deg^2 to detect the radio counterparts to binary-SMBH coalescences. Such an observing strategy is not likely to be unique to this problem. For example, such an observing strategy may be required to localize GW-detected mergers between neutron stars and black holes, where EM counterparts at other wavelengths will likely be difficult to detect (Kyutoku et al. 2015). In the ngVLA era, upcoming detectors of astrophysical neutrinos such as KM3Net/ARCA (Adrián-Martínez et al. 2016) will localize the heretofore unidentified neutrino accelerators to approx. 1 deg^2 regions on the sky, and several models predict variable/transient radio counterparts to sources of neutrino production (e.g., blazar flares, 'dark' GRBs). In this section, I describe the menagerie of variable and transient radio sources that are always expected to be found by the ngVLA in few-deg^2 regions, which will need to be classified in order to find the sources of specific interest. Variability in the radio sky is not empirically characterized at the faint flux densities to be accessed by the ngVLA. Below I consider in turn the contributions from cataclysmic events, scintillating compact AGN, and intrinsic variability in AGN.

Cataclysmic events. The afterglows of core-collapse supernovae are the most common cataclysmic events in the radio sky (for a compilation, see Mooley et al. 2016). Assuming flux-density statistics consistent with a non-evolving population in Euclidean space, $6\,\mathrm{deg}^{-2}$ events are expected peaking over $10\,\mu$Jy. However, besides the relativistic explosions that form $\sim 1\%$ of the supernova population, the variability timescales of radio supernovae will be long (months to decades). Furthermore, the low radio luminosities of radio-supernova afterglows imply a nearby population even for the ngVLA, at redshifts $z \lesssim 0.3$. Approximately $0.01 - 0.1\,\mathrm{deg}^{-2}$ on-axis GRBs and jetted tidal disruption events are expected, which will closely mimic the predicted prompt counterparts from binary SMBHs. At most ~ 1 relativistic explosion is expected to form an interloper in ngVLA observations with $10\,\mu$Jy sensitivity of any given $10\,\mathrm{deg}^2$ region. The host galaxies and redshifts of each interloper radio event will need to be identified, although in many cases multi-wavelength counterparts will be serendipitously identified. Accurate radio localization to ~ 10 mas (to match Gaia-based optical astrometric accuracy) may also enable the locations of sources within host galaxies to be determined, and compared with expectations for the sources of interest.

Scintillating AGN. Spatio-temporal density variations in the Milky Way ionized-ISM cause refractive scintillations of compact extragalactic radio sources. Maximum modulations (modulation indices of order unity) are observed for sources smaller than a few μas, at frequencies between $1 - 10$ GHz off the Galactic plane (Walker 1998), on timescales of several hours. Although compact sources (e.g., observable with VLBI) are a subdominant population below flux densities of 1 mJy (Middelberg et al. 2013), any optically thick synchrotron source fainter than 1 mJy at a few GHz will compact enough to scintillate. Simulations (Ravi et al., in prep) suggest that up to $500\,\mathrm{deg}^{-2}$ scintillating sources $> 10\,\mu$Jy will be observable at 10 GHz. These sources may be identified by (a) higher-frequency observations, where modulation indices will typically be lower, (b) wide-band monitoring to identify unusual instantaneous spectral shapes caused by scintillation, and (c) longer-term monitoring to identify re-brightening episodes.

Variable AGN. Intrinsic variability in compact AGN may be a more insidious interloper class. Mooley et al. (2016) suggest that $\sim 1\,\mathrm{deg}^{-2}$ AGN is expected to vary on timescales of days to years above 0.3 mJy, possibly due to the propagation of shocks internal to jets (Marscher & Gear 1985). This implies the existence of a larger interloper population at the tens of μJy level, given the still-increasing AGN source counts in this flux-density range (e.g., Condon et al. 2012, and Fig. 2 here). Considering the binary-SMBH case in particular, having discarded all interlopers that are not temporally coincident with the GW events, and those that are outside the GW-derived redshift bounds, the only way to distinguish between an internal shock within a pre-existing jet and a newly formed jet shocking an external CNM is by careful modeling of the evolution of the radio source. Such modeling could, for example, distinguish between a shock propagating through a dense, radially varying CNM, and a sparse jet.

4. Technical requirements

Radio observations will continue to be of great value in classifying and characterizing enigmatic classes of extragalactic transients in the ngVLA era. I have considered in particular the example of binary-SMBH coalescence events to be detected by LISA.

Dedicated ngVLA observations of a few to a few hundred coalescing binary SMBHs detected annually by LISA are required for the discovery of their EM counterparts. The localization of the EM counterparts will result in their host galaxies and redshifts being identified, and will unlock their rich astrophysical and cosmological potential. LISA will provide localization regions of $1 - 10\,\mathrm{deg}^2$ in the days to weeks prior to coalescence, and redshift measurements accurate to $O(10\%)$. Prompt transient jets are predicted to be launched upon SMBH-SMBH coalescence, which are likely to shock the CNM, producing radio lightcurves similar to those shown in Fig. 1.The jets are then predicted to eventually stabilize with radio flux density as estimated in Equation 1. For example, for a fiducial off-axis observer orientation, coalescences of $10^8 M_\odot$ SMBHs at $z = 5$ will produce prompt jets with radio flux densities peaking above $10\,\mu$Jy at 10, 30, and 80 GHz, within ~ 10 days of coalescence. The final jets will generally be observable only in more favorable orientations, depending on their Lorentz factors.

From an observational point of view, this report provides specific motivation for the use of the ngVLA to search for individual faint transient/variable sources in up to few-deg^2 regions. Some general technical considerations for this task are discussed below.

Point-source sensitivity. The more sensitivity the better! The diversity of possible sources makes it difficult to specify sensitivity requirements. However, the mooted performance of the ngVLA at centimeter wavelengths, in particular above the 14 GHz limit of the baseline design for SKA1-mid, is highly desirable. Although lower frequencies (e.g., S, C, X bands) are typically used for time-domain work, synchrotron emission from expanding shocks will in several circumstances (particle densities $\gtrsim 10\,\mathrm{cm}^{-3}$, initial expansion velocities $\gtrsim 0.1c$; e.g., stripped envelope core-collapse supernovae, GRBs, TDEs, LISA counterparts) have a synchrotron self-absorption spectral peak that is brighter at higher frequencies at earlier times. Centimeter-wavelength observations therefore enable such events to be detected sooner, and allow for the evolution of the self-absorbed spectrum to be monitored, thus characterizing the expansion velocity, total energy, and the circum-explosion medium density profile.

Survey speed. The ngVLA as defined in Memo #5 will require several pointings to survey few-deg^2 regions for transient/variable sources. For the LISA case, observations to depths of a few μJy will be required. The approximate, optimistic ngVLA survey speeds corresponding to $5\,\mu$Jy rms continuum noise in the 2, 10, 30, and 80 GHz bands are 5.3, 0.9, 0.14, and 0.002 deg^2/hr. Dwell times of $20 - 130$ s per pointing are required, which may motivate an on-the-fly mosaicking approach in some cases. However, it is evident that deep cadenced surveys of few-deg^2 regions will only be feasible with the ngVLA in the 2 GHz and 10 GHz bands, and possibly the 30 GHz band in exceptional cases. In cases where rms noise levels of $\gtrsim 10\,\mu$Jy are sufficient, the dwell times per pointing become small enough that sub-arraying to cover a larger frequency range becomes a possiblity. Otherwise, higher-frequency follow-up of individual sources of interest detected at lower frequencies will be a more practicable strategy.

Angular resolution and astrometry. Wide-field imaging with the highest angular resolution and corresponding astrometric accuracy achievable with the ngVLA is desirable for this science case. The majority of sources near the detection threshold of a naturally weighted image with sub-100 mas angular resolution and few-

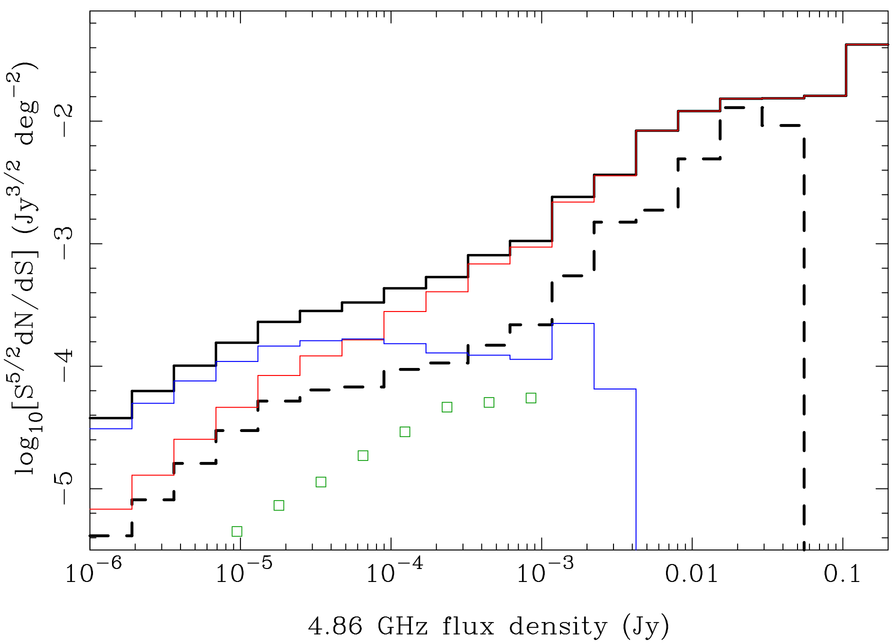

Figure 2. Simulated radio-source differential counts at 4.86 GHz from the SKA Simulated Skies project (Wilman et al. 2008, http://s-cubed.physics.ox.ac.uk). The thick black trace corresponds to all sources, which include AGN cores, hot-spots and lobes (thin red trace), and star-forming galaxies (thin blue trace). Counts of sources with angular extents greater than 50 mas are indicated by the thick dashed black trace. Wide-field imaging with the ngVLA targeting radio transients/variables will thus likely be able to refine candidate lists by factors of $\gtrsim 4$ in a single epoch by excluding extended sources. The green squares correspond to a simulation of the maximum possible counts of sources with angular extents $< 5\,\mu$as, which are likely to refractively scintillate at moderate to high Galactic latitudes (Ravi et al., in prep). Note that the most common cataclysmic-event interloper, core-collapse supernovae, will have $S^{5/2}dN/dS \approx 2\times10^{-7}$ Jy$^{3/2}$ deg^{-2} (Mooley et al. 2016).

μJy sensitivity will be star-forming galaxies and extended (e.g., Condon et al. 2012), and thus separable from the point-like sources of interest. This is demonstrated in Fig. 2, where I compare simulated source counts of < 50 mas objects with the total radio-source population. Astrometric accuracy of ~ 10 mas will further allow for accurate radio-optical image registration in the post-Gaia era, enabling the rejection of some interloper radio-transient events.

Spectral coverage. The characterization of any detected event over the full ngVLA band would be an ideal outcome. In particular, it is important to identify and monitor any continuum spectral peak. Wide-band data are also useful in rejecting interloper events. For example, scintillation of compact sources is mitigated at higher frequencies (typically $\gtrsim 10$ GHz), and can sometimes be identified by unusual spectral shapes. In-band spectral indices will also be useful in source identification.

Triggered, cadenced observing. Finally, the ngVLA use-case presented here will require support for triggered, cadenced observing. Procedures for such observing modes have been honed on the VLA. However, triggered observations have been more difficult to implement with ALMA (Alexander et al. 2017). It is important that policies enabling fast-turnaround proposals and rapidly scheduled observations are included in ngVLA operations planning. Further, tools that enable rapid data reduction by the user community will also be necessary.

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