Radio Continuum Emission from Galaxies: An Accounting of Energetic Processes

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Abstract. Radio emission from galaxies is powered by a combination of distinct physical processes, providing critical information on the massive star formation activity, as well as access to the relativistic [magnetic field + cosmic rays (CRs)] component in the interstellar medium (ISM) of galaxies. Frequencies spanning $\sim 1 - 100$ GHz, which are observable from the ground, are particularly useful in probing these processes. In this chapter we discuss the role a next-generation VLA (ngVLA) will play transforming our understanding of star formation and associated feedback activity in both the nearby and moderate redshift galaxies.

1. Introduction

Radio continuum observations have proven to be a workhorse in our understanding of the star formation process (i.e., stellar birth and death) from galaxies both in the nearby universe and out to the highest redshifts. A next-generation Very Large Array (ngVLA), as currently proposed, would revolutionize our understanding of what powers the radio continuum emission in and around galaxies by enabling the routine construction of $\sim 1.2 - 120$ GHz radio spectral maps. Coupled with its nearly order of magnitude increased sensitivity compared to the current Jansky VLA, the ngVLA makes it possible to use this frequency window to investigate these distinct physical processes for large, heterogeneous samples of galaxies for the first time. Furthermore, by delivering such a finely sampled spectrum over this entire frequency range with a single instrument will allow robust separation of these various emission components, which is currently the main uncertainty for multi-frequency radio studies. Each observation will provide enough sensitivity and spectral coverage to robustly decompose and accurately quantify the individual energetic components powering the radio continuum, thus providing unique information on the non-thermal plasma, ionized gas, and cold dust content in the disks and halos of galaxies.

In this chapter we focus on how the ngVLA can be used to map and decompose the radio continuum emission from heterogeneous samples of nearby galaxies on 10 - 100 pc scales to conduct a proper accounting of the energetic processes powering the various emission components. In doing so, we will be able to determine how star formation, AGN, and physical conditions in the ISM gives rise to varying contributions of:

- non-thermal synchrotron emission powered by accelerated CR electrons/positrons
- free-free emission from young massive (HII) star-forming regions

- anomalous microwave emission (AME), which is a dominant, but completely unconstrained, foreground in CMB experiments.
- cold, thermal dust emission that accounts for most of the dust and total ISM content in galaxies.

At the discussed sensitivity and angular resolution, the ngVLA will be able to both create maps of current star formation activity at 100 pc scales, as well as detect and characterize (e.g., size, spectral shape, density, etc.) discrete HII regions and supernova remnants (SNRs) on 10 pc scales in galaxies out to the distance of the Virgo cluster. Their properties can then be used to see how they relate to the local and global ISM and star formation conditions. Such investigations are essential for understanding the astrophysics of high-z measurements of galaxies.

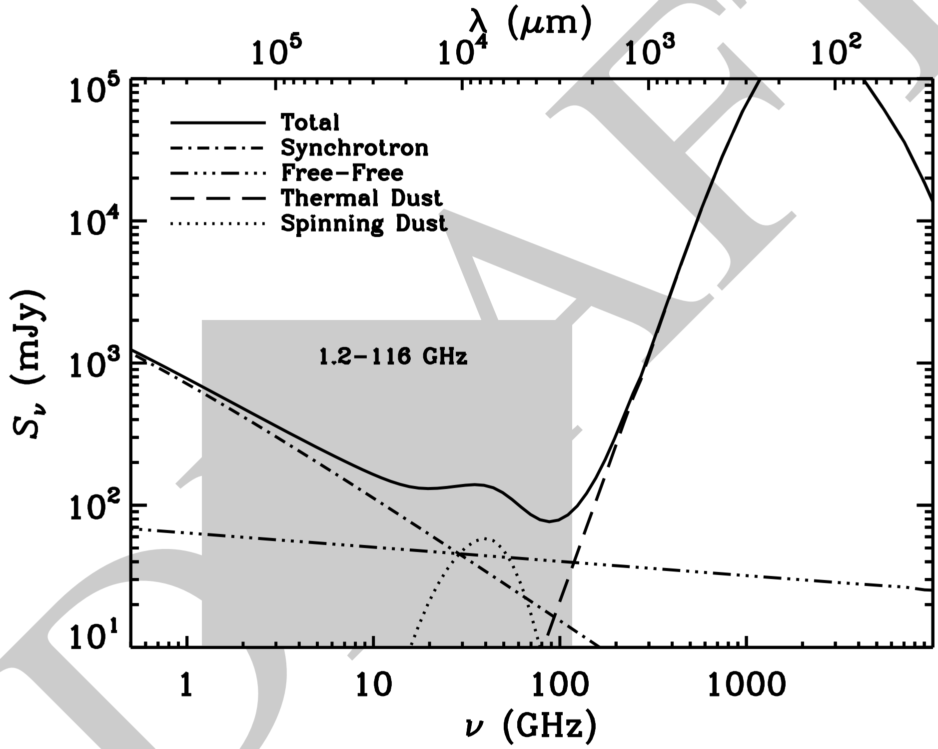

Figure 1. A model spectrum illustrating the various emission processes (non-thermal synchrotron, free-free, spinning dust, thermal dust) that contribute to the observed radio frequency range to be covered by the ngVLA. Only in the proposed ngVLA frequency range ($1.2 - 116$ GHz, highlighted) do all major continuum emission mechanisms contribute at similar levels, making this range uniquely well-suited to next-generation continuum studies.

2. The Energetic Processes Powering Radio Continuum Emission

Radio continuum emission from galaxies covering $\sim 1.2 - 116$ GHz is powered by an eclectic mix of physical emission processes, each providing completely independent information on the star formation and ISM properties of galaxies (see Figure 1). These processes include non-thermal synchrotron, free-free (thermal bremsstrahlung), anomalous microwave, and thermal dust emission. Each of these emission components, described in detail below, are extremely faint in the $\sim 30-120$ GHz frequency range, and therefore difficult to map in the general ISM of nearby galaxies using current facilities. Consequently, current knowledge about the emissions processes over this frequency range is limited to the brightest star-forming regions/nuclei in the most nearby sources, providing no information on how the situation may change in drastically different ISM conditions that may be more representative of conditions in high-redshift galaxies, where we have to rely on globally integrated measurements.

- **Non-Thermal Synchrotron Emission:** At ~GHz frequencies, radio emission from galaxies is dominated by non-thermal synchrotron emission resulting, indirectly, from star formation. Stars more massive than $\sim 8\,M_{\odot}$ end their lives as core-collapse supernovae, whose remnants are thought to be the primary accelerators of cosmic-ray (CR) electrons, giving rise to the diffuse synchrotron emission observed from star-forming galaxies. Thus, the synchrotron emission observed from galaxies provides a direct probe of the relativistic (magnetic field + CRs) component of the ISM. As illustrated in Figure 1, the synchrotron component has a steep spectral index, typically scaling as $S_{\nu} \propto \nu^{-0.85}$ (Niklas et al. 1997). By covering a frequency range spanning $1.2-116$ GHz, the ngVLA will be sensitive to CR electrons spanning an order of magnitude in energy (i.e., $\sim 1-30$ GeV), including the population that may drive a dynamically-important CR-pressure term in galaxies (e.g., Socrates et al. 2008).

- **Free-Free Emission:** The same massive stars whose supernovae are directly tied to the production of synchrotron emission in star-forming galaxy disks are also responsible for the creation of HII regions. The ionized gas produces free-free emission, which is directly proportional to the production rate of ionizing (Lyman continuum) photons and optically-thin at radio frequencies. In contrast to optical recombination line emission, no hard-to-estimate attenuation term is required to link the free-free emission to ionizing photon rates. Unlike non-thermal synchrotron emission, free-free emission has a relatively flat spectral index, scaling as $S_{\nu} \propto \nu^{-0.1}$. Globally, free-free emission begins to dominate the total radio emission at $\gtrsim 30$ GHz (e.g., Condon 1992; Murphy et al. 2012), exactly the frequency range that the ngVLA will be delivering an order of magnitude improvement compared to any current or planned facility.

- **Thermal Dust Emission:** At frequencies $\gtrsim 100$ GHz, (cold) thermal dust emission on the Rayleigh-Jeans portion of the galaxy far-infrared/sub-millimeter spectral energy distribution can begin to take over as the dominant emission component for regions within normal star-forming galaxies. This in turn provides a secure handle on the cold dust content in galaxies, which dominates the total dust mass. For a fixed gas-to-dust ratio, this total dust mass can be used to infer a total ISM mass. Given the large instantaneous bandwidth afforded by the ngVLA, approximately an order of magnitude increase in mapping speed at 100 GHz compared to ALMA (Carilli 2017), such an observations will simultaneously provide access to the $J = 1 \rightarrow 0$ line of CO revealing the molecular gas fraction for entire disks of nearby galaxies. Alternatively, combining HI observations (also available to the ngVLA) with $J = 1 \rightarrow 0$ CO maps, one can instead use the thermal dust emission to measure the spatially varying gas-to-dust ratio directly.

- **Anomalous Microwave Emission:** In addition to the standard Galactic foreground components (free-free, synchrotron, and thermal dust emission), an unknown component has been found to dominate over these at microwave frequencies between $\sim 10 - 90$ GHz, and is seemingly correlated with 100 μm thermal dust emission. Cosmic microwave background (CMB) experiments were the first to discover the presence of this anomalous dust-correlated emission (Kogut et al. 1996; Leitch et al. 1997), whose origin still remains unknown. Its presence as a foreground still hampers studies as the accurate separation of Galactic foreground emission in CMB experiments remains a major challenge in observational cosmology. At present, the most widely accepted explanation for the anomalous emission is the spinning dust model (**?**Draine & Lazarian 1998; Planck Collaboration et al. 2011; Hensley & Draine 2017) in which rapidly rotating very small grains, having a nonzero electric dipole moment, produce the observed microwave emission. The increased sensitivity and mapping speed of the ngVLA will allow for an unprecedented investigation into the origin and prominence of this emission component both within our own galaxy and others, ultimately helping to improve upon the precision of future CMB experiments.

3. Robust Mapping of Star Formation within Nearby Galaxies on a Range of Physical Scales

For a proper decomposition of the radio continuum emission into its component parts, one needs to have spectral coverage at frequencies low enough (i.e., < 10 GHz) to be dominated by the non-thermal, steep spectrum component, having a spectral index of -0.85 (Condon 1992; Niklas et al. 1997; Murphy et al. 2011) and at frequencies high enough (i.e., > 50 GHz) where the emission becomes completely dominated by thermal emission, having a spectral index of -0.1. Given the potential for a significant contribution from anomalous microwave emission (e.g., Murphy et al. 2010; Scaife et al. 2010; Hensley et al. 2015), peaking at frequencies $\sim 20 - 40$ GHz, coarse coverage spanning that spectral region is critical to account for such a feature. To date, the shape of the AME feature is largely unconstrained, and has not been carefully measured in the ISM of extragalactic sources. This is largely due to the insensitivity of current facilities to conduct a proper search for AME in nearby galaxies and map the feature with enough frequency resolution to provide useful constraints on its shape.

Broadband imaging spanning the full ngVLA frequency range of $1.2 - 116$ GHz will therefore be extremely powerful to properly decompose radio continuum emission from galaxies into its constituent parts. By additionally having frequency coverage below 8 GHz provides sensitivity to free-free absorption, which is common in nearby luminous infrared galaxies (e.g., Condon et al. 1991; Barcos-Muñoz et al. 2015). For individual (ultra compact) H II regions, the turnover frequency can be as high as $\approx$20 GHz (Murphy et al. 2010). As a fundamental goal of the ngVLA will to produce star formation maps for a large, heterogenous sample of nearby galaxies at $\approx 1''$ resolution, delivering Hα-like images that optical astronomers have relied on heavily for decades without having the additional complications of extinction and contamination by nearby [N II] emission, making such images extremely difficult to interpret.

By achieving arcsecond-like resolution that is commensurate with ground-based optical facilities, the ngVLA will be able to probe $\approx$100 pc scales out to the distance of Virgo (the nearest massive cluster at $d \approx 16.6$ Mpc), which are the typical sizes of giant molecular clouds (GMCs) and giant HII regions. At an rms sensitivity of 0.15 μJy bm^{-1} at 28 GHz, such radio maps will reach a sensitivity of $\approx 0.005\,M_\odot\,\mathrm{yr}^{-1}\mathrm{kpc}^{-2}$, matching the sensitivity of extremely deep Hα images such as those included in the Local Volume Legacy survey (Kennicutt et al. 2008).

Using the same data, but applying a different imaging weighing scheme to create finer resolution maps (i.e., $0''.1$, or even higher for brighter systems), similar multi-frequency radio continuum analyses can be perofmred for discrete HII regions and SNRs to complement high-resolution, spaced-based optical/NIR observations (e.g., *HST*, *JWST*, *WFIRST*, etc.). At an angular resolution to $0''.1$, the data would sample $\approx$10 pc scales in galaxies out to the distance of Virgo to resolve and characterize (e.g., size, spectral shape, density, etc.) discrete HII regions and SNRs with a sensitivity to diffuse free-free emission of $\approx 0.5\,M_\odot\,\mathrm{yr}^{-1}\mathrm{kpc}^{-2}$.

3.1. Missing Short-Spacings

An additional consideration for these studies is sensitivity to large angular scales and zero-spacing measurements. For studies of discrete HII regions and SNRs, the lack of sensitivity on large angular scales is not a concern. For mapping the free-free emission of nearby galaxies a largest angular scale sensitivity of $1'$ should be adequate for most studies of star formation.

For a Gaussian source of FWHM ϕ, the fringe visibility falls to $^1/_2$ at projected baseline length $b[\mathrm{m}] \approx 1.517 \times 10^3 \lambda[\mathrm{m}]/\phi[']$. The shortest available spacing is the antenna diameter, so the requirement that the fringe visibility be at least $^1/_2$ sets a frequency upper limit of 25 GHz for 18 m dishes for $1'$ FWHM sources.

Of course, having sensitivity on angular scales significantly larger than $1'$ would be better. For diffuse synchrotron and thermal dust emission from nearby galaxies, sensitivity to much larger (many arcminutes) scales may be required, and is likely a limitation of the ngVLA for such studies. Three possible solutions are:

1. A larger single dish (e.g., 3$\times$ an ngVLA dish diameter $\approx$54 m) used in total-power mode to yield all spacings < 25 m. This would be expensive, and combining single-dish and interferometer data has not always worked well.

2. A dedicated, short-spacing array of smaller dishes (e.g., $^1/_3\times$ an ngVLA dish diameter to bring the shortest spacing down to 6 m) would be sensitive to sources up to $3'$ in size (or to $1'$ sources observed at frequencies up to ≈ 50 GHz). This solution is simple and effective, but still is not sensitive to the more extended nearby galaxies.

3. The dedicated short-spacing array of smaller dishes (solution 2) plus one or several individual ngVLA 18 m dishes used in total-power mode to completely fill in the central hole in the (u, v)-plane left by the smaller dishes. Such a "bootstrapping" solution combined with mosaicing is sensitive to arbitrarily large sources and doesn't cost more than the small array.

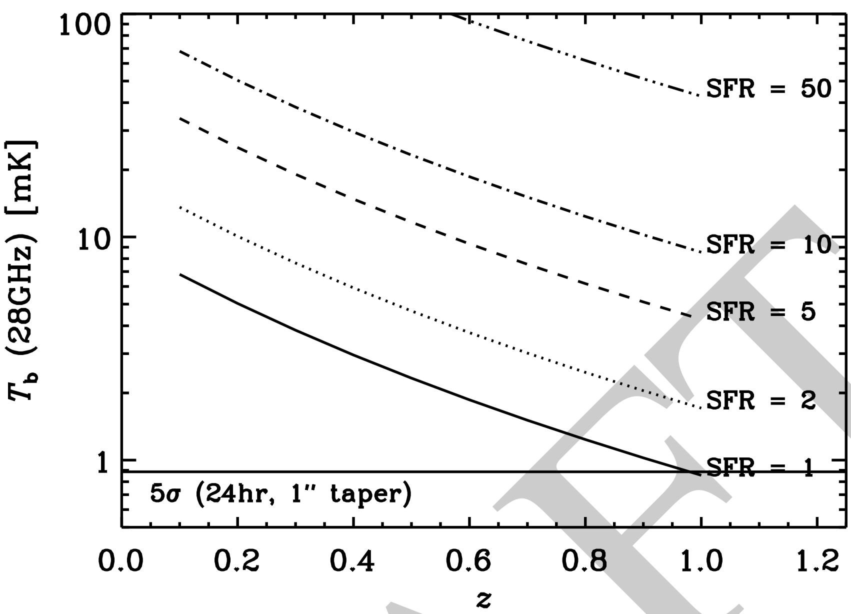

Figure 2. Observed 28 GHz brightness temperature vs. redshift indicating the expected brightness temperature of an 4 kpc disk galaxy forming stars at a rate of 1, 2, 5, 10, and 50 $M_{\odot}\,\mathrm{yr}^{-1}$. Given the current sensitivity specifications, by tapering to a $1''$ synthesized beam, the ngVLA will have enough brightness temperature sensitivity to resolve a Milky Way like galaxy forming stars at a rate of a few $M_{\odot}\,\mathrm{yr}^{-1}$ out to $z \sim 1$ after a 24 hr integration. Using the existing JVLA, the detection of such a galaxy would take ∼2500 hr.

4. A Robust Star Formation Indicator at All Redshifts

With the increased collecting area and bandwidth of the ngVLA, one would be able to measure and resolve rest-frame 60 GHz emission from a Milky Way like galaxy out to $z \sim 1$ forming stars at a few $M_{\odot}\,\mathrm{yr}^{-1}$ after a 24 hr integration. This is illustrated in Figure 2 which shows the observed 28 GHz brightness temperature of 4 kpc diameter disk galaxies with a range of star formation rates. We note that a choice for 4 kpc disk may be slightly conservative, given that the 10 GHz sizes found for μJy sources at $z \sim 1$ in deep JVLA observations of GOODS-N are reported to be ~ 1.2 kpc (Murphy et al. 2017). The $5\,\sigma$ 28 GHz brightness temperature rms of the ngVLA tapered to a $1''$ synthesized beam is based on the sensitivities given in (Selina & Murphy 2017). Accordingly, such observations provide highly robust measurements of star formation rates for comparison with other optical/UV diagnostics to better understand how galaxy extinction evolves with redshift. And, by coupling these higher frequency observations with those at lower radio frequencies one can accurately measure radio spectral indices as a function of redshift to better characterize thermal vs. non-thermal energetics.

5. Uniqueness to ngVLA Capabilities

While the JVLA has frequency coverage up to 50 GHz, it lacks the higher frequencies (> 50 GHz) necessary to measure the location where the radio spectrum is completely dominated by free-free emission, which is required to robustly separate out the various emission components. At the top end of the ngVLA frequency range, cold thermal dust emission associated with the molecular ISM may also be detectable at low surface brightness levels, which can be characterized by a rising spectrum. ALMA does cover this 100 GHz (3 mm) frequency range, but does not currently have spectral coverage below 84 GHz.

More importantly, the lack of sensitivity by the JVLA and other telescopes (e.g., ALMA) makes such continuum mapping for entire galaxies, rather than just the brightest HII regions within them, impossible. It is only with the ngVLA that the full potential of the radio continuum spectrum be used as a tool to properly constrain the various energetic processes that power its emission for a broad range of heterogeneous conditions in galaxies.

6. Synergies at Other Wavelengths

Nearby galaxies provide our only laboratory for understanding the detailed physics of star formation and AGN activity for much larger ranges of physical conditions afforded by our own Milky Way. They are the workhorse for testing and applying physical models of star formation and feedback processes that are used in galaxy evolution models to explain statistical observations for large populations of galaxies at high redshifts, for which it is impossible to conduct detailed astrophysical experiments as being described here. Consequently, the ngVLA observations included in this chapter to illuminate the relation to thermal and non-thermal processes in the interstellar medium will be highly synergistic with observations from shorter wavelength telescopes that have access to large numbers of other diagnostic (line and continuum imaging) that may be difficult to interpret due to extinction at both low and high redshift. The same can be said for synergy with longer wavelength, far-infrared telescopes that will provide access to dust continuum and fine structure line emission that can be used to characterize the cold/warm neutral phase of the ISM.

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