EVLA memo 91

EVLA Phase III: A major step toward the high frequency SKA

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Abstract.

I consider the scientific impact of increasing the EVLA collecting area by an order of magnitude – the EVLA phase III, with an emphasis on high frequency science (> 15 GHz). As a starting point, I use the recently completed science case for the SKA. I consider in detail two SKA key science programs which are fundamentally enabled by the EVLA phase III: (i) the study of redshifted molecular line emission from distant galaxies, into cosmic reionization, and (ii) terrestrial planet formation through imaging of protoplanetary disks. I also include a general list of high frequency science proposed for the SKA.

In comparison with the SKA, two important factors are high-lighted. First, the proposed SKA will have 80 times the collecting area of the current VLA, or 8 times that of the EVLA phase III. However the current maximum frequency specified for the SKA is 22 GHz. Assuming the EVLA phase III has the same frequency coverage as the EVLA (up to 48 GHz), one gains a factor 4 in flux density for thermal emission (constant T_B) going from 22 to 44 GHz. Hence *the sensitivity of the EVLA phase III to thermal emission will be only a factor two lower than that of the SKA*. And second, at fixed spatial resolution the longest baseline can be a factor two shorter at 44 GHz relative to 22 GHz, thereby saving costs in terms of array configuration, connectivity, and data transmission. Overall, much of the high frequency thermal science proposed for the SKA could be achieved with just a factor 10 increase in collecting area to the EVLA, at perhaps only 10% of the cost required for the full SKA collecting area.

1. Introduction

Phase I of the EVLA program entails a major (long over-due) over-haul of the electronic systems – from the receivers, through the LO/IF, to the correlator. EVLA phase I increases the sensitivity by an order of magnitude for continuum observations, mostly through increased bandwidth. It also allows for orders-of-magnitude improvement in spectral line capabilities, in terms of the number of channels and bandwidth. However, phase I provides a relatively small improvement to the sensitivity for a given spectral line (ie. a band-limited signal), through incremental improvements to the receivers and the antennas. EVLA Phase II involves a proposed increase in the maximum connected baselines to 300 km, or 10× the maximum baseline of the current array. The next logical step to the improvement of scientific capabilities for radio astronomy facilities in the 1 to 50 GHz range will be to increase the collecting area of the EVLA by roughly an order of magnitude, commensurate with the improved electronics and baseline coverage.

The purpose of this memo is to highlight the potential science goals for an order of magnitude increase in the EVLA collecting area. While the gains for such a system for spectral line science are obvious, the combined gain in sensitivity due to collecting area and bandwidth, in concert with the increased spatial resolution, enables break-throughs in continuum science as well.

I should clarify two points at the start. First, the assumed factor 10 is not definitive, but should be considered representative of the need for a significant increase in collecting area, similar to the increase from the 3m to 4m class optical telescopes of the 1980's to the 10m class telescopes of today. And second, I do not discuss the telescope element design. Presumably the design will be the most economical that meets the specifications, leveraged off of the existing telescopes and infrastructure of the EVLA phases I and II.

A 10$\times$ larger EVLA is a natural intermediate step toward the eventual goal of the Square Kilometer Array (SKA), in particular for the higher frequency SKA programs. The SKA represents an 80 fold increase in collecting area relative to the current VLA. The SKA project has recently released an extensive science case, including chapters on a wide range of currently topical astrophysical programs, and a set of the key programs of highest scientific import which drive the telescope design (Carilli & Rawlings 2004).

I adopt the SKA science case as representative of the science areas currently considered topical and where radio astronomy provides a fundamental contribution. I then consider what one order of magnitude increase in collecting area to the EVLA would provide in terms of addressing the SKA Key Science Programs. I focus on two programs for which the higher (cm) frequencies of the EVLA phase III are critical: (i) molecular line emission from the first galaxies, and (ii) terrestrial planet formation. I also include a 'laundry list' of other high frequency science projects from the SKA science case. Note that I do not repeat the detailed science arguments behind these programs, since these are readily available (Carilli & Rawlings 2004).[1]

2. SKA Key science programs – EVLA phase III contribution

2.1. Dark ages: cosmic reioinization and the first luminous objects

One major contribution of cm telescopes to the study of the earliest galaxies comes through observations of CO and other molecular spectral lines (Carilli et al. 2004). The lower order transitions of the classic (rest frame) mm transitions for common interstellar molecules redshift into the cm bands for distant galaxies.

There are two important factors to keep in mind when considering EVLA phase III studies of high z molecular line emission. First, when considering the very first galaxies, into the epoch of cosmic reionization (the EoR; $z > 6$), mm telescopes such as ALMA will be limited to studying very high order transitions, eg. at $z = 6$ the lowest ALMA band (80 – 100 GHz) redshifts to 690 GHz, corresponding to CO 6-5, or HCN 7-6. It is unclear that these higher order transitions will be excited in an average galaxy, in particular for the high

[1] www.skatelescope.org/pages/page_astronom.htm

dipole moment molecules such as HCN, since the required densities for excitation become extreme ($> 10^5$ cm^{-3}).[2]

Second, the SKA design specification entails a factor 80 increase in collecting area relative to the current EVLA, and a factor 8 relative to the EVLA phase III. Also, the current SKA design specification has a 22 GHz maximum frequency, with a goal of 35 GHz. Assuming the EVLA phase III has the same frequency coverage as phases I and II implies that EVLA phase III will go up to 48 GHz.[3] For thermally excited lines (ie. constant T_B)[4], the velocity integrated line flux increases as the square of the frequency. This implies that the EVLA phase III observing CO 2-1 at 45 GHz ($z = 4$) has only a factor two lower sensitivity to a total molecular gas mass as the SKA observing CO 1-0 at 22 GHz.

Figure 1 shows the sensitivity to molecular line emission for the VLA, the EVLA phase III, and ALMA. Also shown is a rough model for the expected continuum and CO line emission from an active star forming galaxy with a total IR luminosity $\sim 10\%$ that of Arp 220 at $z = 5$, corresponding to a star formation rate of a few 10's $M_\odot$ $year^{-1}$. Such a galaxy would be comparable to the Ly-break galaxies seen in deep optical surveys, ie. characteristic of the high z galaxy population. I have assumed a CO excitation ladder similar to that seen in the few high z molecular line emitting galaxies currently known (see footnote 4).

Figure 1 shows that the EVLA phase III will be able to detect the CO 1-0 and 2-1 emission from relatively 'normal' star forming galaxies out to very high redshifts, into the epoch of cosmic reionization. ALMA will easily detect the higher order transitions, if they are excited. ALMA will also be able to study the low excitation fine structure line emission from primeval galaxies ([CII] 158μm, [OI] 63μm). These lines are thought to be the dominant ISM coolants.

Centimeter telescopes also detect non-thermal radiation associated with massive star formation in galaxies (Condon 1992). The relationship between radio continuum emission and star formation has been clearly established via the tight radio-FIR correlation for star forming galaxies, and radio-FIR photometric redshifts have become a standard tool in the study of dusty, star forming galaxies at high redshift. Radio observations provide a dust-unbiased view of galaxy formation.

Figure 2 shows the sensitivity of the VLA, EVLA phase III, ALMA, and the JWST to radio continuum emission from distant galaxies. EVLA phase III

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[2]The CMB will also contribute to excitation. For example, at z=6, T(CMB) = 19K, while the typical CO excitation temperature in an active star forming galaxy is $\sim$ 30 to 40K.

[3]50 GHz is the natural upper frequency limit for a cm telescope, set by the transmission of the atmosphere (the wings of the 60 GHz O_2 line).

[4]Peak flux density increases as frequency^2 for constant T_B. For normal galaxies, such as the Milky Way, constant T_B holds for the integrated CO emission roughly up to CO 3-2, above which sub-thermal excitation can occur. Note that in many of the high z molecular emission line galaxies discovered to date constant T_B holds up to CO 5-4 or so, with a roll-off to higher transitions. However, there is a strong selection bias in current samples, in which all of the systems were selected as extreme starburst and/or AGN galaxies, and molecular lines were first observed using mm telescopes. No sample currently exists selected on the basis of lower order CO transitions.

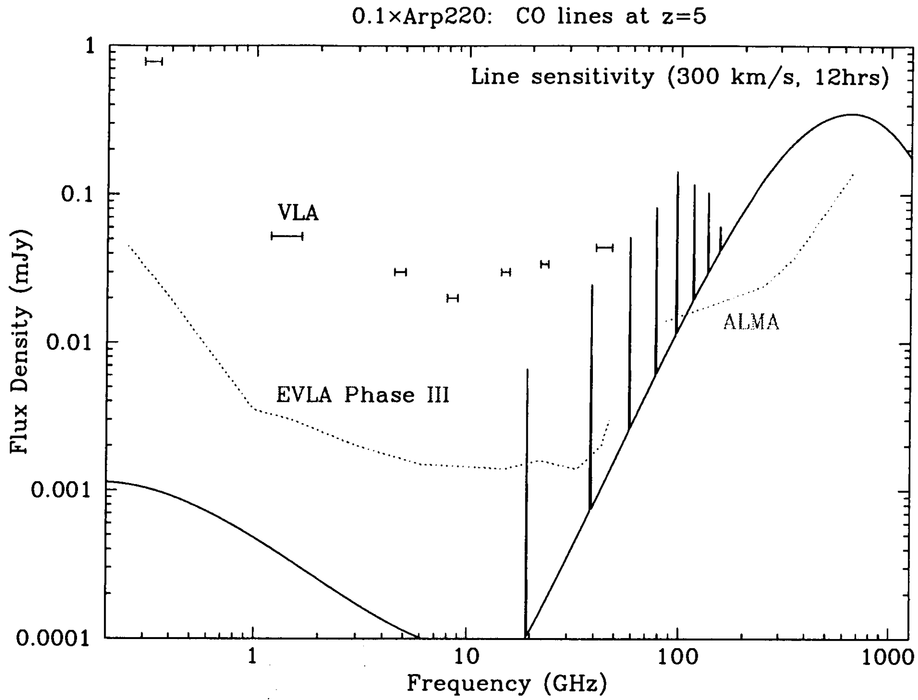

Figure 1. The dotted curves show the (1σ) sensitivity to spectral line emission for the VLA, EVLA phase III, and ALMA in 12 hours. The solid curve is the emission spectrum, including continuum and CO lines, for a source with 10% the luminosity of Arp 220 (ie. a source with FIR $\sim 10^{11}$ $L_{\odot}$) at $z = 5$.

will open up the study of normal star forming galaxies into the EoR, and provide the necessary complementarity to ALMA and the JWST.

It should be emphasized that proper study of galaxy formation requires observations across the electromagnetic spectrum. Optical and near-IR observations reveal the ionized gas and stars. Far IR through (sub)mm observations reveal the dust, higher order molecular line emission, and low excitation fine structure line emission. The higher cm frequencies reveal the lower order molecular transitions, which provide the best estimates of total gas mass. And at longer cm wavelengths one observes synchrotron emission, which is a dust-unbiased measure of the star formation rate and distribution. Overall, the EVLA Phase III and ALMA provide the necessary complementarity to large ground and space-based optical and IR telescopes, enabling a panchromatic study of the formation of normal galaxies back to the EoR. In particular, the mm and cm studies are most useful for studying galaxies in their earliest, dust-enshrouded stages of formation.

2.2. Terrestrial planet formation

The SKA science advisory committee recognized terrestrial planet formation as one of the key science programs for the SKA. The main program entails imaging thermal emission from protoplanetary disks on sub-AU scales, ie. the

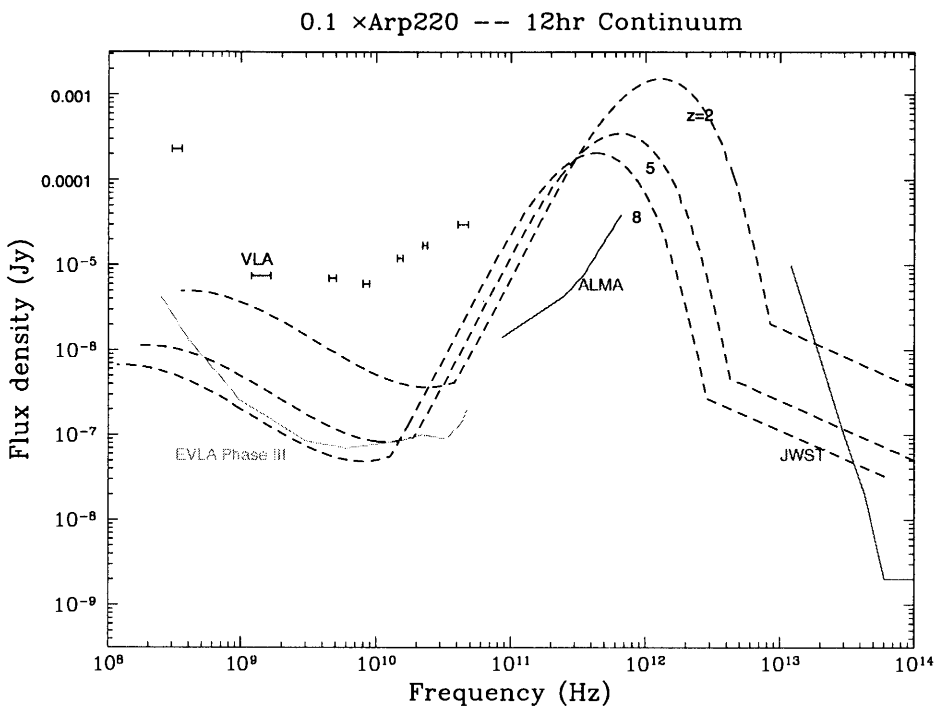

Figure 2. The solid curves show the (1σ) sensitivity to continuum emission for the VLA, EVLA phase III, ALMA, and the JWST, in 12 hours. The dashed curves are the continuum emission spectrum for a source with 10% the luminosity of Arp 220 (ie. a source with FIR $\sim 10^{11}$ $L_\odot$) at z = 2, 5, and 8.

scales relevant to terrestrial planet formation. A spatial resolution of ≤ 7 mas is required to obtain sub-AU resolution at the distance of the nearest active star forming regions (eg. Orion, Taurus at 150 pc), or baselines $\sim$ 400 km at 22 GHz, with brightness temperature sensitivities of about 10K.

Wilner (2004) considers the study of protoplanetary disks in the context of terrestrial planet formation. The planet generates a gap in a protoplanetary disk on sub-AU scales, which can be detected as the absence of thermal emission from the dust and debris. Moreover, the observed structures in the disk are expected to evolve on orbital timescales ($\sim$ 1 year). Calculations, and current observations, suggest that the depth of these gaps should be of order 10 to 100 K at 22 to 43 GHz.

EVLA phase III could make significant progress on this program prior to the SKA in a number of ways. First, increasing the high frequency limit to 43 GHz from 22 GHz decreases the required maximum baselines by a factor two, to 200 km, well matched to EVLA phase II geometry. This also reduces the costs of array configuration, connectivity, and data transmission.

Second, as with the redshifted CO arguments above, the EVLA phase III at 43 GHz will be competitive with the SKA at 22 GHz in terms of sensitivity to thermal emission. For instance, the rms at 43 GHz in 12hr for phase III of the EVLA is about 0.14 uJy, corresponding to 7.5 K at 3.5 mas resolution.

For comparison, the SKA brightness temperature sensitivity at 22 GHz at this resolution is 3.7 K.

Two points are important to bear in mind. First, the EVLA phase II has the necessary resolution, but insufficient sensitivity to image disk-gaps on sub-AU scales without very long integration times (100's hours), thereby limiting study to only a handful of extreme systems.

And second, the study of protoplanetary disks is one of the major science drivers for ALMA. ALMA has easily sufficient sensitivity to detect the total dust and molecular line emission from proto-planetary disks. However, in terms of spatially resolved imaging, ALMA will be limited to imaging disks on scales larger than a few AU, for two reasons: (i) at the shorter (submm) wavelengths these systems are thought to be optically thick on scales larger than an AU, such that one cannot observe all the way down to the sub-AU scale structures. And (ii) at longer wavelengths, where the overall optical depth may be low enough to see down to sub-AU scales (250 GHz and below), ALMA's spatial resolution will be coarser than 10 mas.

Overall, ALMA will provide key insights into planet formation on larger scales, including all the molecular line and SED diagnostics so critical for physical interpretation of protoplanetary disk evolution and planet formation. But only the EVLA phase I+II+III provides the unique combination of spatial resolution (< 5 mas) and brightness temperature sensitivity (7.5 K in 12hr), required to image the secular evolution of protoplanetary disks down to terrestrial (sub-AU) planet scales.

3. Other SKA high frequency science goals

Following is a list of the general SKA science programs that stated the need for frequencies ≥ 15 GHz. The first authors of the relevant chapters are listed parenthetically. See Carilli & Rawlings (2004) for details.

- Large (pre-biotic) molecules and astrobiology – DNA precursors like glycine (Lazio, Hoare, Tarter)
- Galactic center pulsars – orbits around Sgr A* and tests of strong field GR (Kramer, Cordes)
- Extragalactic magnetic fields – Faraday rotation studies of distant galaxies (Gaensler, Beck)
- Extragalactic water masers – constraining H_o to 1%, studies of AGN supermassive black holes and their accretion disks on sub-pc scales, proper motions of local group galaxies using VLBI (Greenhill, Morganti, Fomalont)
- Sunyeav-Zeldovich effect at 30 GHz – evolution of large scale structure (Burigana)
- Molecular absorption line systems at intermediate and high redshifts – evolution of the fundamental constants of nature (α, μ, g_p), and astrochemistry in primeval galaxies (Curran, Blain)

- Stellar (SiO, H_2O) masers – late stages of stellar evolution and stellar envelopes (Marvel)
- Solar system thermal emission – planetary atmospheres, surfaces, asteroids, KBOs, comets. etc... (Butler)
- Spacecraft tracking and telemetry at 32 GHz – movies from Mars (Jones)

References

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