A DESIGN CONCEPT FOR A VERY LARGE ARRAY SKY SURVEY

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ABSTRACT

We argue the merits of a extra-galactic survey of $\sim 20,000$ deg$^2$ in the B-array of the Jansky Very Large Array to a $5\sigma$ depth of 0.1 mJy (20 $\mu$Jy rms) at 2–4 GHz (S-band). Such a survey would provide VLA-COSMOS depth imaging, but with $20,000 \times$ the area and would be expected to yield of order 25 million sources. Time requirements are less than 10% of the total lifetime of LSST, but would provide crucial radio support for next-generation optical/IR surveys such as Pan-STARRS, SkyMapper, DES, SuMIRe, VST/VISTA, and, of course, LSST by overlapping these areas as much as possible.

1. Introduction

While deep, pointed observations are crucial for understanding the details of our Universe, large-area sky surveys provide the laboratories in which these experiments are conducted. The Sloan Digital Sky Survey (SDSS) and the Faint Images of the Radio Sky (FIRST) surveys provide clear examples of how sky surveys can expand our existing knowledge and drive discovery in new directions. Each new generation of surveys has greatly increased our knowledge of the cosmos and has led to the discovery of heretofore unknown phenomena. Today we are on the edge of a new age in optical surveys with the genesis of Pan-STARRS, SkyMapper, DES, VST/VISTA, and SuMIRe. Ten years from now, the Large Synoptic Survey Telescope will begin constructing the definitive large, deep optical map of the Universe. These surveys will probe new realms by covering large areas of sky to depths as faint as 28th magnitude with multiple epochs allowing new time-domain discoveries. Yet without multiwavelength support, these surveys will fail to live up to their full potential as observations that span the electromagnetic spectrum are crucial for completing the picture of most astronomical sources.

The FIRST survey (Becker et al. 1995), with an area matching that of SDSS and
relatively high resolution, provided a long-wavelength bandpass to the nominal SDSS $ugriz$ survey. It is in that vein that we outline a radio survey using the Jansky Very Large Array (JVLA) that is complementary to the next generation of optical surveys. The combined surveys will allow us to address fundamental questions in the evolution of galaxies, the star formation history of the universe, and the demographics and growth of supermassive black-holes. This project would provide a legacy database of $\sim 25$ million radio sources to sub-milliJansky flux densities and allow for measurements in the sub-microJansky regime (through image stacking).

Here we lay out some basic principles that are important desiderata for any large-scale survey with the JVLA in the era of ground-based synoptic surveys in the optical. The basic premise herein is that a VLASS would be of maximal utility to the broader astronomical community if it is optimally synergistic with existing and next generation ground-based imaging surveys in the optical and IR. We consider the issues of areal coverage, resolution/array, depth, and bandpass separately. However, these are not independent choices and will be considered together within the context of the total time a survey with optimal choices in each would need.

2. Resolution/Array

Arguably the most important question for any VLASS is that of what resolution such a survey should be performed at. Issues of source confusion between optical/IR surveys and any VLASS would be minimized by using a bandpass/array combination that achieves a resolution that is roughly comparable to ground-based optical surveys (with sub-arcsecond resolution). In the optical, this criterion is, in part, to measure the shapes of galaxies for weak lensing experiments, so a VLASS perhaps need not have quite the same resolution. However, the resolution should be within a factor of 2–3 of these surveys in order to maximize the utility of cross-band object matching.

Relatively high resolution is crucial for matching the depth of new optical surveys.
For example the cumulative number counts of galaxies per square arcminute goes as
\[ N = 46 \times 10^{0.31 \times (i-25)} \] (LSST Science Book), which means that we would expect \( \sim 2 \) galaxies with \( i < 24 \) (LSST single-epoch depth) in the 10” beam of ASKAP (for example [GTR: treating the FWHM as the radius, not sure if that is the appropriate comparison]) and nearly 14 galaxies with \( i < 26.8 \) (LSST co-added depth). The density of stars varies considerably with position, but, averaged over the sky, is comparable to the density of galaxies. Thus it is clear that a VLASS must have a resolution equal much better than ASKAP to minimize source confusion issue in order to provide maximal utility with respect to LSST and other such ongoing surveys.

Of course, we must consider that high resolution leads to “over-resolving” of extended sources. However, this problem is mitigated in a number of ways. First is that Ivezić et al. (2002) find that the fraction of radio sources with complex morphology is only \( \sim 10\% \). Second is that the NVSS survey (Condon et al. 1998) already provides a low-resolution survey (to a limit of \( \sim 2.5 \) mJy) at 20cm (L band; 1.4 GHz). Similar back-up for future over-resolution will come from ASKAP itself whose beam of 10” and an L-band rms of 10 \( \mu \) Jy will provide crucial calibration for bright extended sources.

A resolution roughly double that of FIRST will provide an excellent match to the relative astrometric accuracy in the optical. FIRST had astrometric accuracy of \( \sim 1” \)—better than the typical seeing of SDSS (and only a few times worse than the astrometric accuracy). Next-generation optical surveys will have seeing that is roughly twice as good and a VLASS should attempt to match that improvement. Further improvement in resolution is unnecessary and perhaps unwarranted given the reduction in photometric accuracy for extended objects that comes with higher resolution. However, it must be emphasized that good resolution is key. For example, Figure 1 from Hodge et al. (2011) shows that there is information to be gained from improvement in resolution over FIRST.

Furthermore, the comparison to the FIRST resolution is only relevant for 10,000 deg\(^2\) of sky. For the rest of the sky visible to the VLA, the appropriate comparison is to the NVSS
Fig. 1.— A-array (top) observations of SDSS quasars observed with FIRST in the B array (bottom). (Condon et al. 1998), which has a resolution 10× lower. This is important as up to 30% of NVSS sources are resolved into multiple components by FIRST. In terms of matching to catalogs at other wavelengths, this is an important consideration as the weighted mean position of multiple sources renders the nominal astrometric accuracy meaningless for these blended sources.

Given the desire for higher resolution than FIRST, we are driven to either L-band observations in the A-array (1′′3), S-band observations in either the A or B arrays (0′′65, 2′′1, respectively) or C-band observations in either the A or B array (0′′33, and 1′′0, respectively). As A-array resolution in any of the L-, S-, or C-bands is perhaps higher than is needed (and indeed prudent given the problem of over-resolution), we consider the B-array a better choice.

3. Bandpass

NVSS and FIRST both observed in the L-band (1.4GHz; at low- and high-resolution, respectively). A new, deeper L-band survey could be conducted much faster since the JVLA has a bandpass (in L) of 1 GHz instead of 50MHz—20× wider. Thus naively redoing the FIRST survey today would take just 1/20th of the time (about 10 days!). In practice
the full bandwidth is not available due to radio frequency interference (RFI) and may be more like 600 MHz. However, the same was true for FIRST as well, so while the usable bandpass might not be the full 1GHz, the usable bandpass relative to what was usable for FIRST should still be $\sim 20 \times$. Furthermore, as RFI is worst on the equator due to satellite interference; we might expect a larger usable bandwidth for fields away from the equator.

L-band provides relatively low spatial resolution in the B-array, so it is important to consider higher frequency bandpasses (we do not consider lower frequency as the resolution is worse). At 3GHz, S-band provides $2 \times$ the resolution (with a nominal bandpass of 2GHz) of L-band and C-band (GHz) provides $4 \times$ the resolution (with a nominal bandpass of 4GHz). Arguments regarding total survey time (below) lead us to suggest that S-band is an optimal choice for a VLASS. RFI in the S-band should be no worse than in the L-band and perhaps somewhat better, giving an effective JVLA S bandpass of 1.5GHz—roughly $40 \times$ that of the effective VLA L bandpass.

Lastly it is crucial to realize that the size of the JVLA bandwidths mean that any new survey will yield radio “color” information that was not available in prior single-band observations with the VLA. We illustrate this in Figure 2 where we show that the S bandpass is roughly as wide as the combined $g$ and $r$ bandpasses of SDSS. As a result S-band observations will allow for the determination of radio colors from a single observation, providing crucial information on the shape of the radio spectrum.

4. Depth

The depth for a VLASS should be decided, based on the depth of existing radio surveys, the science that they cannot do, and the desired science to be done. For example at the FIRST survey’s approximate flux limit of $\sim$1mJy, White et al. (2007) find that only 10% of SDSS quasars are detected by FIRST. Historically new surveys are considered to be most cost effective if they reach an order of magnitude deeper than the previous generation. Thus an obvious goal would be $\sim$0.1mJy (100µJy). This is the depth of the VLA-COSMOS
Fig. 2.— Quasar Spectral Energy Distributions from the radio to X-ray. Light gray lines show the mean radio-quiet (solid) and radio-loud (dashed) quasar SEDs from Elvis et al. (1994). A radio-to-optical spectral index of $\alpha_{ro} = -0.2$ is the approximate dividing line between objects traditionally classified as radio loud and radio quiet ($\log R = 1$). We also show the range of spectral indices in the radio and optical bandpasses and between the optical and X-ray bandpasses. At the bottom of the figure, the VLA L, JVLA S, SDSS $r$, and SDSS $g$ bandpasses are depicted at $z = 0$ (black) and $z = 3$ (gray). Note that the JVLA S-band is as wide as SDSS $g$ and $r$ combined, allowing determination of radio colors from a single observation.

survey (Schinnerer et al. 2007), thus we can use the 1800 sources per square degree from VLA-COSMOS to estimate the number of sources. For flat-spectrum ($\alpha = 0$) sources, the S- and L-bands achieve the same relative depths. For steep-spectrum sources ($\alpha = -1$), S-band is a factor of 2 shallower. On the average, we’d expect S-band to be about 40% shallower, thus we might expect of order 25 million radio sources to a depth of $\sim 0.1\text{mJy}$ in the S-band over an LSST-equivalent area of 20,000 $\text{deg}^2$. [GTR: Assumes that
I can scale 1800 linearly down by 40%.

Using stacking analysis and deeper VLA imaging White et al. (2007) find that a 10-fold increase in depth would allow detections for ~50% of SDSS quasars (include formally “radio-quiet” quasars). Indeed Kimball et al. (2011) have used deep radio observations to show that the AGNs contribution to radio flux extends much deeper than the limit of FIRST. Stacking analysis would further complete the picture of the quasar radio sky to sub-microJansky depths.

Between the realms of high-probability detections and stacking of undetected sources, it is also possible to perform “forced photometry” on the JVLA maps, extending our catalog below the typical 5σ detection limit. Normally it is dangerous to probe low-significance detections, especially when there are so many beams on the sky and therefore so many 3σ “detections”. However, this process is much more robust when coupled with accurately known positions from optical and IR surveys. A 3σ detection at the location of a confirmed optical/IR source is highly like to be real and can enable a real gain in the depth of the radio survey for many applications (e.g., Lang et al. 2009).

5. Areal Coverage

Finally, a VLASS will have maximal public utility if it overlaps existing and future large-area sky surveys in the optical/IR. Ideally it would cover as much area as is observable from Socorro, NM that is within the fields of SDSS, Pan-STARRS, SkyMapper, DES, SuMIRe, VISTA/VST, and LSST. Figure 3 shows a comparison of the depth and area covered for major existing and future optical/IR sky surveys, including the HSC-wide area (SuMIRe), DES, PS1, and LSST. As a comparison, FIRST covered over 10,000 deg² within the SDSS footprint, while NVSS covered the full sky north of δ = −40°. With a southern bias in the next-generation surveys, probing as far south as possible is crucial. While it would not be possible to cover the full LSST area (δ >~ −60) given the differences in hemispheres of the observatories, a survey covering −30° < δ < 30° is 50% of the sky or approximately
20,000 deg². Concentrating on extra-Galactic science and avoiding the Galactic plane itself would allow some of that 20,000 deg² coverage to be northward of $\delta = 30^\circ$.

Fig. 3.— The limiting magnitudes (in $r$) and solid angles of existing, on-going, and planned optical imaging surveys.

6. Total Time

There is a tradeoff between the choice of bandpass, areal coverage, and the total survey duration. In all, the FIRST survey took 4000 hours ($\approx 5.5$ months). Thus a VLASS would certainly be feasible if it took as much time as FIRST and was able to cover more area and/or to a greater depth than FIRST. Indeed an investment of 4000 hours represents only 5% of the survey time that will be devoted to LSST over the course of its lifetime of 10 years.
If we wished to double the resolution from the FIRST survey (which was 4.5′′—much worse than the resolution of LSST), both the S-band (in A or B array at 0′65 and 2′1 resolution, respectively) or the C-band (in B array at 1′ resolution) would be acceptable choices.

An S-band survey would need 4× as many pointings as FIRST, as the angular extent of the VLA beam scales inversely with frequency. However, the wider bandwidth, in principle, will achieve the same depth 40× faster, making the survey take 1/10th of the time as FIRST. Thus a depth of 10× FIRST over 10,000 deg² is potentially achievable in the same amount of time as FIRST.

A C-band survey in the B array would provide 1′′ resolution—intermediate between the two S-band options. Moreover, the C-band has double the bandwidth of the S-band—allowing the same survey in 1/2 of the time and with twice the lever arm for determining spectral indices (between 4 and 8 GHz). The number of pointings to cover the FIRST area, would, however, also be larger—roughly 20× as compared to 4×. As the increase in bandwidth (double) over the S-band is more than offset by the larger number of pointings needed (5×), we consider an S-band survey in the B array to be more efficient than a C-band survey in the B array. Thus we are led to a natural choice of a S-band survey in the B array. Figure 4 shows a sample pointing configuration for such a survey following the pattern that worked so well for FIRST and NVSS.

Taking B-array and S-band as fixed parameters, we now consider the trade-offs between areal coverage, depth, and total survey time. While the VLASS web site\(^1\) gives a nice breakdown of the survey times for each passband, the assumed depth of 100 µJy in each passband does not make for a realistic comparison to FIRST, being only 1/3 deeper. Thus we provide a table with some more realistic scenarios with area between 10,000 and 20,000 deg², depth between 15 and 20 µJy, and survey times spanning 4000 to 8000 hours.

\(^1\)https://science.nrao.edu/science/surveys/vlass/documents/VLASurveyCapabilities_v1.pdf
Fig. 4.— RMS noise resulting from a possible pointing grid. Pointing centers (yellow) are on a hexagonal grid with 10 arcmin spacing. The grayscale image and contours show the noise in coadded maps after summing across the 2 GHz bandpass (assuming 0.5 GHz is lost to interference). The grid spacing is chosen to give good uniformity of coverage even at the highest frequency (4 GHz) and so has considerable overlap between fields at the lowest frequency (2 GHz). [GTR: Say how rms changes from best to worst. 10%??]

of clock time. For values with a range, the first number is computed by scaling from the FIRST survey parameters, while the 2nd number is derived by scaling from the VLASS web site. In each case two each of area, depth, and time are held fixed and the other values are computed accordingly. For the FIRST comparisons we hold fixed the slewing and RFI overhead, allowing the efficiency to vary with the time on sky. For the VLASS web site
comparison, we instead hold fixed the overhead at 25% (75% survey efficiency). The first 3 entries assume nominal values of 10,000 deg$^2$, 15 $\mu$Jy, and 5000 hours, where we have held two of those values fixed and have computed the actual value of the 3rd parameter.

For the 4th entry, we ask what depth could be achieved if we desired to cover twice the area of the FIRST survey using as much as twice the time allotment for FIRST. We find that, achieving a 5$\sigma$ depth of 10\times FIRST (100 $\mu$Jy at $\sim$20 $\mu$Jy rms) over an area equivalent to that covered by LSST would require about 8000 hours of time. While such a large time block would necessarily take away from other observations, it is worth noting that survey observations come with an impressive level of efficiency ($>70\%$). Such a large legacy proposal will take a lot of time, but it will be minimally wasteful in its drive to create a legacy radio survey comparable to the next-generation of optical/IR surveys. Moreover, considering large sky surveys as a sort of an electronic-VLA, the efficiency of such observations are even higher as each unique query of the resulting object catalog can be considered as an observation that need not be done (and a proposal that need not be written). [MAS suggests cutting the last sentence, others have asked for more specifics. Maybe just state some facts? RLW can provide.]

Table 1. FIRST-like S-band VLASS Survey Parameters

<table>
<thead>
<tr>
<th>Area (deg$^2$)</th>
<th>Depth ($\mu$Jy)</th>
<th>Time (hours)</th>
<th>Exposure (s)</th>
<th>Efficiency (%)</th>
</tr>
</thead>
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<td>10000</td>
<td>15</td>
<td>4631–5041</td>
<td>41.25</td>
<td>76</td>
</tr>
<tr>
<td>10650–9300</td>
<td>15</td>
<td>5000</td>
<td>41.25</td>
<td>76</td>
</tr>
<tr>
<td>10000</td>
<td>13.67–16.13</td>
<td>5000</td>
<td>45.28</td>
<td>77</td>
</tr>
<tr>
<td>20000</td>
<td>18.08–20.17</td>
<td>8000</td>
<td>34.22</td>
<td>73</td>
</tr>
</tbody>
</table>
7. Considerations for the VLASS Survey Science Group

[GTR: Not everyone has liked these, but I think it is useful to bring up issues for the SSG to talk about in the context of what we are outlining. Even if they are dead horses.]

Within the context of the outlined program there are a number of issues that merit consideration of the VLASS Science Survey Group (SSG). Three specific areas that we identify here are related to the choice of array configuration, dealing with wide bandwidths, and the impact to JVLA scheduling.

The standard VLA configurations are A, B, C, and D with hybrid BnA, etc. configurations during transitions. Each configuration is used for approximately 4 months before the next change. Developing a new array design for a survey would be inefficient if it were not going to be used for at least this much time. However, as any VLASS is likely to require more time than is available in any one configuration per cycle, it may worth reconsidering the array design and perhaps establishing a special hybrid “survey” configuration.

Related to this is the need for the VLASS SSG to determine how to best schedule any large block of time. One option would be to get it all over with at once, providing an immediate legacy survey that could be used for follow-up targeting of next-generation imaging surveys should spectroscopic capabilities come to fruition. Clearly a new hybrid array design would be efficient in this case. Another possibility would be to devote an extra ~1.5 months to the JVLA cycle in each of the appropriate array configurations for the next decade, enabling the survey to finish before LSST gets fully under way.

Lastly we note that the large bandwidth presents challenges in addition to the benefits noted above as it might not be straightforward to combine data taken at 2GHz and 4GHz (nor is it likely that the full bandpass will be uncontaminated). Thus the width of the bandpasses is another issue that the VLASS panel should consider in detail. In practice the 2GHz bandpass is broken into 16 IFs of 125 MHz each and the resolution from one end to
the other changes by a factor of two. The data can be reduced in each IF separately, but some care would be needed to combine them together in order to treat them as a single observation.

8. Science Topics

[MAS: Need to justify large area. GTR: I’m not so worried about that now, just looking into what is possible and what people think is interesting. For myself, depth is more important than area. But if others have good area justification, please say so.]

8.1. Radio-Loud Quasars

The primary demand that quasar science—at high redshifts in particular—places on a radio survey is for a wide area. Quasars are rare, and the radio-loud sources account for only $\sim 5\%$ of the population as a whole. To SDSS depth, the surface density of optically selected quasars is $\sim 43\,\text{deg}^{-2}$ at $0 < z < 5$ (Richards et al. 2006; Ross et al. 2013); of which only $\sim 1.4\,\text{deg}^{-2}$ are at $z > 3$. Thus only one high-redshift, radio-loud quasar is detected per $\sim 7\,\text{deg}^2$ of survey area (the number counts are not sufficiently steep at faint fluxes to argue for a lower flux limit). Building a large statistical sample of radio sources for demographical studies of, for example, the evolution of radio loudness with redshift (Jiang et al. 2007) requires a nearly all-sky survey.

Not only is a large area required, so is significant depth. For example, while the physics that leads to the generation of huge radio lobes in radio-loud quasars still eludes us, it seems clear that black hole mass (e.g., Lacy et al. 2001) and spin (e.g., Blandford & Znajek 1977; Blandford & Payne 1982) play key roles in this question. Better coupling could be made to the detailed physics of black hole accretion if we had a deeper census of the demographics of radio-loud quasars. Jiang et al. (2007) have argued that the radio-loud fraction (RLF) goes down with increasing redshift and with decreasing luminosity. We show
these trends using an updated sample of quasars in Figure 5. However, the robustness of these $L$ and $z$ trends is sensitively dependent on the completeness of the FIRST survey near its flux limit. While models of quasar evolution can explain these trends (major mergers both feeding and spinning up BHs with lower redshift; Volonteri et al. 2013), testing these results with much deeper data is crucial for our understanding of not only radio-jets, but black hole physics in general.

High-resolution observations are also important for understanding of radio-loud quasars. The typical spectral index for a radio quasar is $\alpha \sim -0.5$. Although this is relatively flat, it still argues for lower frequencies in order to achieve higher sensitivity for a given flux limit. In addition, there are hints that compact, steep-spectrum radio emission may be more prevalent at high redshifts (e.g., Frey et al. 2011). Such sources will be easily detected by planned low frequency ($< 1$ GHz) surveys with excellent sensitivity; however, these surveys will invariably have poor resolution. Efficient matching of radio sources to surveys at other wavelengths (particularly in the optical) requires $\sim$arcsecond resolution. In this way, a higher frequency VLA survey can provide an essential complement to the low frequency surveys, providing localization of radio sources at a much greater depth than FIRST. This is prerequisite to identifying candidates for spectroscopic campaigns to obtain redshifts, either in the optical/near-IR, or with ALMA.
The combination of FIRST and SDSS provides an example of a radio survey well-matched to an optical imaging/spectroscopic survey in depth and resolution. FIRST detections matched to counterparts in the SDSS imaging received spectroscopic fibers during the survey, and the number of radio quasars with redshifts increased dramatically (Schneider et al. 2010), particularly at high redshift. However, even though the SDSS was relatively shallow, FIRST was not complete in terms of radio-loudness for typical SDSS quasars. Using a definition of radio loudness as \( \log(f_{5\text{GHz}}/f_{2500}) > 1 \) (Stocke et al. 1992), FIRST was only sensitive to radio-loud SDSS quasars with \( i < 19.0 \), predominantly the bright, low redshift \( (z < 2) \) sample. Obviously a deeper survey with the modern VLA would significantly improve this situation, but trade-offs with frequency must be considered.

For a typical radio source with a spectral index of -0.5, the flux at 3 (5) GHz will be roughly two-thirds (half) of that at 1.4 GHz. Nonetheless, at a depth of 0.1 mJy, a higher frequency survey would reach quasars roughly seven (five) times fainter in the radio than those in FIRST. In terms of radio loudness, an S-band survey would be sensitive to all radio-loud quasars with \( i < 21.1 \), while a C-band survey would reach \( i < 20.8 \) (the deeper S-band limit corresponds to \( \sim 30\% \) increase in quasar number counts at \( 2.2 < z < 3.5 \) and \( \sim 23\% \) at \( 1 < z < 2.2 \) relative to the C-band limit, Ross et al. 2013). Thus a new VLA survey would detect radio emission from all radio-loud quasars in the SDSS spectroscopic catalog \( (i < 20.2) \), a large number of radio-intermediate sources, and many of the new spectroscopic quasars in the BOSS catalog \( (2.2 < z < 3.5, r < 22) \) and the upcoming eBOSS \( (0.9 < z < 2.2, r < 22) \). It is worth noting that although BOSS extended the depth of FIRST source targeting by nearly 3 magnitudes relative to the SDSS, a paltry 4% of BOSS quasars appear in the FIRST catalog (Pâris et al. 2013). Clearly, a next-generation survey is needed to explore the radio properties of these large quasar samples.
8.2. Radio-Quiet Quasars

While only about 5% of SDSS quasars meet a formal definition of being radio-loud, it is increasingly clear that even radio-quiet quasars are not radio-silent. Stacking analysis (White et al. 2007) of formally radio undetected objects can be used to explore the radio properties of the other 95% of quasars and suggests that increasing the depth of the radio sky by a factor of 10 over an area as big as the SDSS survey will lead to a detection of a factor of 10 times as many objects in the radio.

An open question is whether this radio flux is intrinsic to the AGN or is due to star formation. Results from Kimball et al. (2011) based on just 179 quasars suggests both: those radio-quiet quasars well below the established “radio loud” dividing line are likely to be dominated by star formation. However, it is also likely that the radio-loud division is excluding objects that, while not displaying classical properties of radio-loud sources, are still dominated in the radio by AGN-related processes.

Better radio catalogs that complement next-generation optical surveys will be crucial to developing a full understanding of the radio contributions within AGN populations.

8.3. Spectral Indices

[Brotherton]

8.4. High-$z$ Quasars

Haiman, Quataert & Bower (2004) predict from models of dark matter halo formation that radio-loud quasars may be visible to $z \gtrsim 10$; they calculate a surface density at 20 $\mu$Jy of 2 to 5 deg$^{-2}$ (depending on spectral index) at $z \sim 10$. Detection of even a single object at this redshift would help to illuminate the Dark Ages. They also estimate one bright ($\sim 1$ mJy) object at $z \sim 8$ in every 3 to 10 deg$^2$; again, the detection of a single such
object would allow the direct measurement of 21 cm absorption throughout the epoch of reionization.

Fan and McGreer to provide. For now placeholder is from the SuMIRe proposal.

8.5. Star-Forming Galaxies

The well-known correlation between star formation and radio emission means that our survey will also be a highly sensitive probe of the star formation history of the Universe. While it is known that the rate of star formation has dropped dramatically since redshift 1, its dependence on cosmic epoch in the redshift range 1-2, when galaxies were undergoing their final assembly, is quite uncertain because of the effects of dust on traditional optical and UV measurements of the star formation rate. Our radio observations are insensitive to this dust and, when coupled with photometric redshifts, will allow us to measure in an unbiased way the star formation rate as a function of cosmic epoch.

Maybe Rick, Mark, and/or Amy can help here? The above taken verbatim from SuMIRe proposal.

8.6. Stars

We can estimate the number of stellar radio source detections from the Chandra COSMOS fields, which recorded X-ray emission from 60 stars in 0.9 deg$^2$. Using the X-ray-radio scaling relation of Guedel & Benz (1993) we can expect YY radio star detections.

Who could provide something for this? Placeholder taken verbatim from SuMIRe proposal.
9. Conclusions

If the JVLA were to carry out another large sky survey, a number of important decisions will need to be made as the capabilities of the facility to perform vastly different types of sky surveys greatly exceeds the time available. The basic tenet that we set forth in this whitepaper is that such a survey will have maximum value to the astronomical community if it is designed in a way that best supports the next-generation of imaging surveys in the optical/IR. We would argue that this also allows for great science to be done using the radio data alone. Given the science goals of these surveys (quasars, supernovae, baryon acoustic oscillations, galaxy clusters—all at high-redshift) we have argued that relatively high resolution in the radio is important. We have further argued that the S-band is the logical new survey band for the JVLA with an optimal trade off of bandwidth and beam size. The wide bandwidth of the new S-band means that, in a single observation, a new survey could effectively reproduce previous VLA surveys in both the L-band and C-band (instead of just L-band), doubling the efficiency of such observations and allowing key science using radio spectral indices. Reaching a depth of ~0.1mJy at relatively high resolution would enable the survey to effectively act as an additional long-wavelength bandpass for next-generation optical/IR imaging surveys, providing an important legacy data product for both the radio and optical/IR communities.
REFERENCES


This manuscript was prepared with the AAS \LaTeX{} macros v5.2.