EXPLORATION OF THE DYNAMIC RADIO SKY

K. MOOLEY[1],
CO-ADVISORS: S. R. KULKARNI[1], D. A. FRAIL[2] & G. HALLINAN[1]

Submitted November 5, 2012

ABSTRACT

Owing to the dearth of high-cadence, blind surveys at sub-mJy levels in the radio, our view of the dynamic radio sky at GHz frequencies is rather limited. I propose a thesis consisting of an extensive study of the variable and transient sources in the radio sky on timescales between seconds and years. This study will utilize radio data from several surveys and data at other wavelengths (X-ray through radio) for the follow-up and characterization of individual sources. The thesis will feature several projects aimed at the exploration of the four-dimensional phase space (parametrized by areal density, brightness, timescale and emission frequency) of radio variables and transients. Two projects (one submitted for publication and the data from the other being analyzed) involve planning out and executing a wide-shallow radio survey, developing reduction and analysis techniques for the vast amounts of radio-survey data as well as the use of multi-wavelength data (follow-up/archival) for understanding the nature of radio sources. In these projects, we investigate the dynamic nature of the sky at 1.4 and 3 GHz on days-weeks-months and year-long timescales to show that (i) the areal density of transients is at least an order-of-magnitude less than previously estimated, (ii) $\leq$1% of the sources are variable at 1.4 GHz, (iii) the areal density of variables and transients appears to increase with observing frequency, and (iii) above $\sim$100μJy, variability associated with galaxies appears to be nuclear (AGN-like). The reduction/analysis techniques developed in these projects will be applied in the next two projects: (i) searching for transients in all of the VLA archival data (in progress), and (ii) COSMOS-2 radio survey (starting Nov 2012). The former will allow us to probe wider in terms of area, and the latter to delve deeper in terms of flux density, thus allowing us to probe rare and low-brightness source-populations respectively. Another project being planned on these lines (starting 2013) is the transient search in the EVLA calibrator fields which provides improved sensitivity and cadence and gives us access to different observing frequencies, owing to the enhanced capabilities of the Jansky VLA. The final project (starting Nov 2012), based on dividing long-duration EVLA observations into short-integration images, will explore the short-timescale (seconds-hours) regime, which is a completely unexplored part of the phase space. Taken together, the components of this thesis will shed new light on the different types of variable/transient sources at GHz-frequencies, the nature of their emission, and their characterization in terms of areal density, intrinsic brightness, and variability timescale. This work will be the forerunner for the surveys planned for WSRT/Apertif, ASKAP and MeerKAT.

1. INTRODUCTION

Many classes of astronomical objects are known to be variable or transient radio sources, including the Sun, the planets, cool stars, young stellar objects, stellar binary systems, neutron stars, supernovae, gamma-ray bursts and active galactic nuclei. There have been extensive studies of these objects using targeted surveys, but few blind, unbiased surveys for such dynamic radio phenomena. In terms of blind surveys, the largest science yield has come from single-dish radio telescopes, which have surveyed the sky for pulsed and periodic emission from pulsars and related phenomena on typical timescales of milliseconds to seconds. In contrast, interferometric imaging surveys, which are best-suited to probe longer timescales. As such, the dynamic radio sky remains a rich area for discovery (Fender & Bell 2011; Cordes et al. 2004; Cordes 2007).

Here, we make a distinction between sources which are normally above the flux density limit (which we term "variable" and "non-variable", depending on whether or not changes in their flux density are detectable from epoch-to-epoch, although most radio sources are intrinsically variable to some degree) and those which have no quiescent radio counterpart (which we term "transient"). The latter are often explosive events. In this work, we are interested only in the so-called *long-duration* or *slow* variables and transients, which are defined as having timescales greater than about one second.

Stars often exhibit variable radio emission (eg. Güdel 2002), as do pulsars (eg. Archibald et al. 2009), microquasars (eg. Miller-Jones et al. 2009), and AGNs. AGNs make up almost all of the sources seen in imaging surveys above a few mJy at 1.4 GHz. However, our knowledge of the variable GHz sky is especially lacking at sub-milliJansky flux density levels. For *persistent* sources, there is a well-known flattening of the Euclidean-normalized radio source counts below about 1 mJy, corresponding to a change in the radio source populations. This flattening is likely due to the emerging importance of star forming galaxies and low-luminosity AGN at redshifts of order unity in the sub-milliJansky source counts (Condon 2007; Seymour et al. 2008; Smolčić et al. 2008; Padovani et al. 2011). Thus, while variability studies above milliJansky levels are dominated by radio-loud AGN with compact, flat-spectrum components (Sadler et al. 2006; Lovell et al. 2008) variability at these deeper flux density levels may probe new source populations.

Somewhat more is known about transients. On the short timescales there are pulsars (Cognard et al. 1996), and rotating radio transients (RRATs, McLaughlin et al. 2006), Crab nanosecond pulses (Hankins et al. 2003), bursting soft-

[1] Cahill Center for Astronomy, MC 249-17, California Institute of Technology, Pasadena, CA 91125
[2] National Radio Astronomy Observatory, Socorro, NM 87801

gamma ray repeaters (Cameron et al. 2005; Gaensler et al. 2005), transient pulsed emission from magnetars (Camilo et al. 2006) and the short-duration gamma-ray bursts (Fox et al. 2005).

The known long-duration transients are flares seen from AGNs (Falcke & Biermann 1999) at one end of the size scale, to M dwarfs (Jackson et al. 1989), brown dwarfs (Berger et al. 2001; Hallinan et al. 2007), gamma-ray bursts (eg. Frail et al. 2000) and radio supernovae (eg. Brunthaler et al. 2009), as well as source populations discovered in just the last decade, including a transient jet in a dwarf nova (Körding et al. 2008), a new population of sub-relativistic supernovae (Soderberg et al. 2010), a mysterious population of galactic center bursters (Hyman et al. 2005, 2009), and relativistic outflows from tidal disruption events (Zauderer et al. 2011; Cenko et al. 2012).

However, with few exceptions, most of what we know about the transient radio sky has come via radio follow-up of objects identified by synoptic telescopes at optical, X-ray or gamma-ray wavelengths. The small number of high-cadence, blind surveys conducted at sub-milliJansky levels in the radio (Frail et al. 2003; Carilli et al. 2003; Bower et al. 2007) have provided a rather limited view of the long-duration radio sky at GHz frequencies.

Figure 1 shows the variable and transient objects on a timescale vs. luminosity plot from which is evident that this 2-D parameter space is relatively unexplored. Below, I describe our plan to use data from different radio surveys to map out the four-dimensional phase space. The search and characterization of radio variables and transients is outlined in §2 and §3 respectively. In each of these sections, we begin by providing the current paradigm of variables and transients, and then go on to describe the projects which will further our understanding of the dynamic radio sky. I conclude by summarizing the science yield from the projects and the timeline of future events and publications (§4). A summary of projects comprising the PhD thesis are listed in Table 1.

2. SEARCH FOR VARIABILITY OF RADIO SOURCES

2.1. *Current Paradigm and Outstanding Problems*

Variability studies in the past[3], have mainly probed bright radio sources. At 1.4 GHz, only a few percent of the mJy-level sources are significant variables. From 5 GHz surveys we find that the percentage of variables is slightly larger (upto 30%). Carilli et al. (2003) have carried out the only published variability study at sub-mJy sensitivities, where they find that only ∼1% sources at 1.4 GHz have ≥50% fractional variability. As such, from a very small sample of blind surveys carried out in the past, it appears that at GHz frequencies, variability increases strongly with frequency. However, for AGN-dominated samples above 1 mJy, variability at frequencies of a few GHz or below is thought to be dominated by refractive interstellar scintillation, and not by intrisic changes in the source (Gaensler & Hunstead 2000; Ofek et al. 2011).

In the context of extragalactic sources, for a disk galaxy we expect there to be steady emission from diffuse synchrotron emission and the sum of all supernovae. Intrinsic variability can be induced by (i) a stellar explosion (supernova, low-luminosity GRB), and (ii) nuclear radio emission (AGN). Mapping the radio emission to the center of the galaxy would

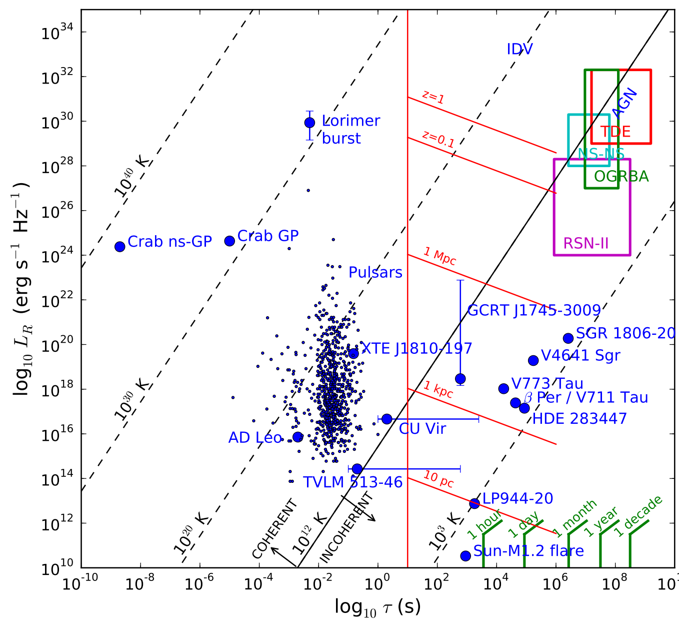

FIG. 1.— The parameter space for radio transients, luminosity density vs. timescale, monitored at GHz frequencies (except for pulsars, which are surveyed at 400 MHz). The timescale shown here corresponds to the transient duration or pulse width. In the Rayleigh-Jeans approximation, $L_R \propto \tau^2$. The brightness temperature, is indicated by the diagonal lines, with $T = 10^{12}$ K marking the maximum brightness temperature of incoherent processes. Examples of known radio transient sources are indicated, including giant pulses (Karuppusamy et al. 2010) and nanosecond pulses from the Crab pulsar (Hankins et al. 2003), radio pulses from XTE J1810197 (Camilo et al. 2006) and other pulsars from the ATNF database [a], radio flares from V4641 Sgr (Hjellming et al. 2000), the brown dwarf LP 944-20 (Berger et al. 2001), the magnetar SGR 1806-20 (Gaensler et al. 2005; Cameron et al. 2005), V773 Tau (Massi et al. 2002), the RS CVn and Algol systems β Persei and V711 Tau respectively (Richards et al. 2003), the WTTS star HDE 283447 (White et al. 1992), Ap/Bp star CU Vir (Trigilio et al. 2000; Lo et al. 2012) and flare star AD Leo (Osten & Bastian 2008); the Galactic center radio transient J17453009 (Hyman et al. 2005), the Lorimer burst (Lorimer et al. 2007) and pulses from the ultracool dwarf TVLM 513-46546 (Hallinan et al. 2007). For this PhD thesis, we are interested in the long-duration timescales, i.e. greater than ∼10 second, marked by the red vertical line. The typical sensitivity of our VLA projects to sources at distances of 10 pc, 1 kpc, 1 Mpc, and $z = 0.1$ and $z = 1$ are also shown with red lines. Colored rectangles represent the predicted values for different long-duration transients such as type-II radio supernovae (RSN-II), Orphan Gamma-Ray Burst Afterglows (OGRBA), neutron star coalescence (NS-NS) and Tidal Disruption Events (TDE).

[a]http://www.atnf.csiro.au/people/pulsar/psrcat/

favor (ii) whereas if the radio emission is mapped to the disk then (i) is favored. The sub-mJy population consists of roughly equal numbers of radio-quiet AGN and star-forming galaxies, and the question that whether variability at these flux density levels is probing star-formation is still open ended. Unlike previous blind surveys, a multi-wavelength approach involving the use of optical images and spectra should be utizlized to identify the source of the emission (AGN activity, star-formation, etc.).

Some AGNs exhibit intra-day variability scintillation of extremely compact components due to extrinsic screens, likely located in our own Galaxy (Lazio et al. 2008; Koopmans et al. 2003). This can cause flux changes ranging from a few percent, to up to 50% in so-called extreme scattering events (Fiedler et al. 1987).

Targeted observations of radio-loud AGNs have shed some light on AGN variability. Flares associated with compact sources are consistent with shock-in-jet models where shocked regions of material propogate at relativistic speeds

[3] See http://www.astro.caltech.edu/%7Ekunal/projects/dynamicRadioSky.htm for a full list and details of past studies

TABLE 1
LIST OF PROJECTS

Project	ν GHz	Area deg^2	Direction (deg)	N$_{\rm ep}$	$\Delta\theta$ ($''$)	δt	Δt	rms (mJy)	Sources	Status
E-CDFS	1.4	0.3	$\alpha = 45.5, \delta = -27.8$	49	2	5 hr	1 day–3 months	0.03	850	Completed
COSMOS-2	2.9	2	$\alpha = 10.0, \delta = 2.2$	77	1	3 min	1 day–4 months	0.03	$\sim$3000	Start in Nov 2012
Stripe-82-L/S/C	1.4/2.9/4.8	50	329$< \alpha <$353,$|\delta| < 1.1$	$\sim$4	3	38 sec	1 week$\sim$1 yr	0.07	$\sim$5000	Proposal/In Progress/Proposal
EVLA-Fast	1.4 - 8.4	$\sim$0.1/field	targeted	1000s	3	$\sim$10 sec	10 sec$\sim$100 hr	$\sim$150	$\sim$10/field	Start in Nov 2012
VLA-Archival	1.4 - 43	$\sim$1500	all-sky	2$\sim$1000s	0.1-200	sec$\sim$min	1 min$\sim$10 yr	0.01-50	$\sim 10^4$	In progress
EVLA-Calib	1.4 - 43	$\sim$0.1	3C48/138/147/286	100s	1-10s	$\sim$1 min	1 min$\sim$3 yr	0.06	$\sim$50	Start in 2013

Notes$-$ $\Delta\theta$ is the resolution (FWHM of the synthesized beam); $N_{\rm ep}$ is the number of epochs; δt is the time span over which each epoch is obtained (see text); Δt is the range of time separations between epochs; Sources is the number of persistent sources detected.

down the jet. The minimum timescale in such events can be as short as $\sim$1 day (Marscher & Gear 1985). On timescales of months, radio synchrotron emission is sometimes seen to vary in correlation with optical (Arshakian et al. 2010) or X-ray (Marscher et al. 2002) emission, as uneven accretion rates from the in-spiraling disk propagate through to knots in the outflowing jets; on timescales of years, even more substantial variations in the accretion rate, heating of material, and reprocessing of energy released in the accretion disk can occur. Long-term variability of very bright AGNs (S$\geq$1 Jy) has been systematically explored (e.g. Aller et al. 1992), but there has not been systematic characterization of the fainter AGN population.

The fractional variability among Galactic sources is seen to be somewhat larger. Becker et al. (2010) find that $\sim$1.6 deg^{-2} of Galactic sources (having flux densities 1-100 mJy at 5 GHz) are strong variables on a timescale of less than years. Fractional variability is larger among these sources than extragalactic objects, since more than 50% are variable by a factor greater than two, compared to the $\sim$1% for extragalactic objects in the same flux density range. The spectral indices of many of these sources are flat or inverted. While a few are associated with young star formation activity, the identity of the majority is unknown.

Furthermore, on account of computing limitations, variability in large surveys have till date been analyzed for timescales larger than several hours. However, thanks to Moore's law, we have entered an era where variability on timescales of seconds to hours in large surveys can be thoroughly explored (note that the pulsar searches are different since they search for periodicity and dispersion measure). Hence, these small timescales are practically unexplored.

2.2. *Projects for Exploring the Variable Radio Sky*

Among the projects listed in Table 1, four will systematically explore the variability of radio sources as part of my PhD thesis, viz. E-CDFS, COSMOS-2, Stripe-82-L/S/C, and EVLA-Fast. A brief plan of each of these projects is given below.

The first project (completed and submitted for publication; Mooley et al. 2012) has explored the variability among sources in the Extended Chandra Deep Field South (E-CDFS) region using archival data from the Very Large Array (VLA). Using 49 epochs of E-CDFS observations at 1.4 GHz sampling timescales from one day to 3 months, we found that only a fraction (1%) of unresolved radio sources above 40 μJy are significant variables. This is consistent with previous studies at 1.4 GHz. The fractional variability at sub-mJy levels is seen to be the same as that at higher flux densities in spite of the known transition of radio source populations below one milliJansky. Among all the variable sources (at this frequency and to a completeness of $\sim$100 μJy), the radio emission originates from the nucleus of an AGN or star-forming galaxy, indicating nuclear activity as the source of variability. Also, a comparison with a 5 GHz survey (Ofek et al. 2011) well-matched to ours, which found upto 30% of sources above 1.5 mJy to be significant variables, suggests that radio variability increases substantially with observing frequency.

With the Stripe-82-L/S/C project we will study the variability of sources at different GHz frequencies as well as timescales. This 50 sq. deg. survey has already been carried out earlier this year in the S-band (3 GHz) in three epochs separated by 1 week and 1 month. The greatest advantage of carrying out a radio survey in the SDSS Stripe-82 region is that there is a plethora of multi-wavelength archival data (photometric as well as spectroscopic) through which we can understand the nature of radio sources. This data is still being calibrated and analyzed, but through a preliminary analysis we have found several significant variables in our data, greater than the 1% seen at 1.4 GHz. We are also spectroscopically following-up variable sources (with Palomar/Keck) to classify them as AGN, star-forming galaxies or galactic objects, and to find their redshift. Next year, we will be proposing for L band (1.4 GHz) and S band observations with EVLA, the L band data to match the depth of Hodge et al. (2011) and the S band data to match our combined reference image from 2012. A comparison with previous L band surveys of this region (White et al. 1997; Hodge et al. 2011) will allow us to find sources variable on timescales of up to 2 decades. We also plan to observe at C band (5 GHz) in two epochs. Overall this amounts to a 100 hr VLA observing proposal for next year.

COSMOS-2 will be a deep extragalactic dataset having a few thousand galaxies ($\bar{z} \simeq 1$, as with COSMOS-1) roughly half of which will be AGN and others star-forming. The first epoch with the EVLA will be in late November, where my role will be to build-up on the existing EVLA data-reduction pipeline to make it an automated transient-finding machine. The greatest advantage of the COSMOS-2 EVLA survey is that it achieves very high sensitivity ($\sim$2μJy), a high cadence ($\sim$1 day) and the optical data from HST (down to V=27 mag) from COSMOS-1 is well-matched with it. Hence we will be able to find optical counterparts to almost all our radio sources. There are similar deep surveys of the COSMOS field at other wavelengths, which makes source-characterization even simpler. One specific science question which we will be able to answer using the HST images is whether the radio variability is nuclear, or associated with the disk of the associated galaxy. This can be done by looking at the radio source position with respect to the optical center of the associated galaxy (as demonstrated in our E-CDFS work).

Finally, the EVLA-Fast project will also explore the unexplored by using all the large (E)VLA archived datasets to probe variability on timescales ranging from several seconds to ∼100 hours. Long integrations will be broken down into several short-exposure (∼10 sec) images. Note that this is a collaboration between several people at Caltech, and even though I will be playing a significant role in this project, I will only co-author the EVLA-Fast papers.

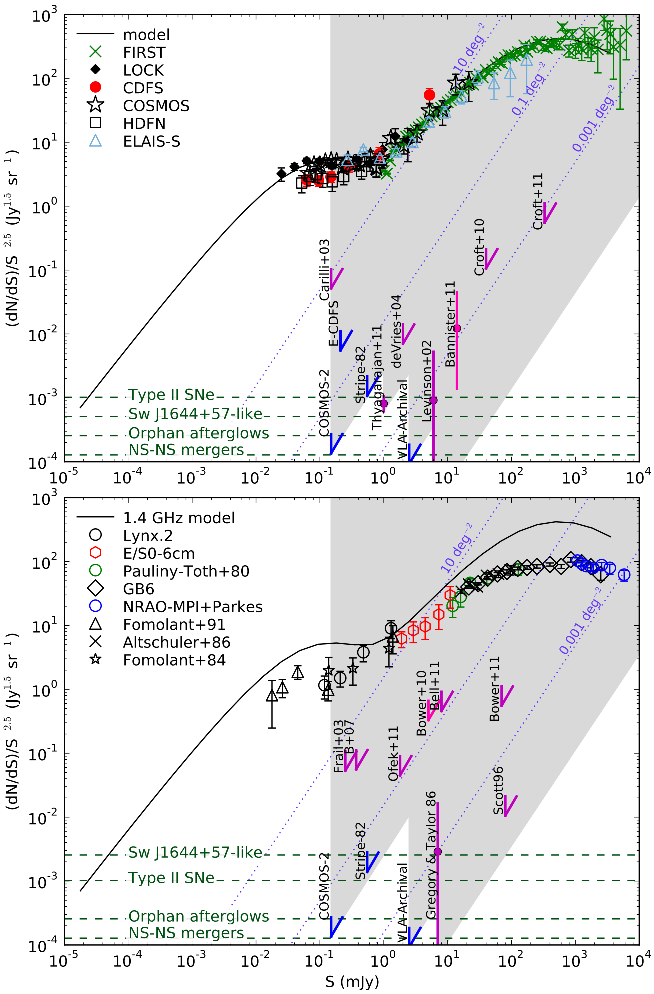

FIG. 2.— Euclidean-normalized differential radio source counts for persistent sources from de Zotti et al. (2010) (top=1.4 GHz, bottom=5 GHz) and the normalized areal density of transients (or limits) as a function of flux density for various surveys at these frequencies. Most of the surveys are upper limits (wedge symbols) and the sampled phase space is shown by the grey shaded area. Blue wedges indicate projects which are planned as part of this PhD thesis. Note that the logN-logS phase space sampled by EVLA-Calib is the same as that shown for Stripe-82. Three surveys have transient detection so far, 2σ error bars for which are shown here. The black solid line is the model for AGNs and star-forming galaxies from Condon (1984). Lines of constant areal density are shown as blue dotted lines. The horizontal dashed lines are estimates for the areal density for known and expected classes of long-duration radio transients are based on Frail et al. (2012), assuming a homogenous distribution in (Euclidean) space.

3. SEARCH FOR RADIO TRANSIENTS

3.1. *Current Paradigm and the Unexplored Territory*

Radio supernovae (RSNe), Tidal Disruption Events (TDEs), Orphan Gamma-Ray Burst Afterglows (GRBAs), compact star coalescence, stellar flares, etc. are among the long-duration radio transients which have been sought-after in past searches. Many of the variability surveys discussed in the previous section were also sensitive to these transients. The results of several of these transients surveys are superposed on the radio source-count plot of Figure 2 (upper panel is for 1.4 GHz and the lower is for 5 GHz). Light-grey shaded areas represent the transient phase space covered by each of the surveys, white space represents the unexplored part of the phase space. With few exceptions most of these transient surveys result in upper limits. Also shown are the normalized areal density of several known and expected classes of long-duration radio transients, based on Frail et al. (2012). Three surveys have transient detections till date, but since they are all searches carried out on archival data, the nature of the transients which they found remains unknown (due to the inability to follow-up these transients in time; except for one transient from Levinson et al. (2002) where the the source was found to be a probable radio supernova by Gal-Yam et al. (2006)).

Radio transient searches have had many false starts due to the the inability to distinguish noise from real sources. According to Frail et al. (2012), the true transient rates appear to be least an order of magnitude below those reported previously by Bower et al. (2007). Real-time data-reduction and rapid follow-up of sources is necessary in order to reduce the number of false positives as well as to get an early understanding of the nature of the transient source.

As such, searches for long-duration transients need to become mature (as compared with the optical). Currently, a logical plan for exploring the different transient source populations seems to be lacking. We need to build a coherent picture by systematically mapping out the 4-D phase space of transients.

3.2. *Projects for Exploring the Transient Radio Sky*

All the projects listed in Table 1 will systematically search for transients. To maximize the chances of finding transients, we need to probe the maximum volume with a survey, which is achieved with a wide-shallow survey (see Appendix). However, if we want to probe transient populations concentrated at large distances (redshifts), it is best to do a narrow-deep survey. To characterize radio sources, we often need optical data which is well matched to the sensitivity of the radio survey. Hence, probing deeper in flux density space need not be the best strategy. This is another point to consider while designing a radio survey. Below, we outline our plan for exploring the phase space of transients with each of these projects. The areal-density coverage for these projects are shown in Figure 2 as blue wedges.

The E-CDFS project is complete, and the major contribution of this work has been in terms of: (i) establishing the areal density of radio transients; we find that the true transient rates appear to be least an order of magnitude below those reported previously, thus confirming the claim by Frail et al. (2012). (ii) characterizing the effectiveness of source-finding algorithms in terms of reliability and completeness since, for transient search, we are interested in sources which are present only in one or a few epochs and can be easily confused with noise spikes in the image. This is crucial for future transient surveys.

Three epochs of the our Stripe-82 S-band survey are complete, and we have found found 6 transients on timescales of 1 week and 1 month. This wide-shallow survey has successfully demonstrated our ability to reduce huge EVLA datasets

($\sim$250 Giga Bytes) in a matter of a few hours, and follow-up the transients with optical spectroscopy with minimal lag. In this respect, we are at an advantage to past transient searches which have relied on archival data. Another unique feature of this project is the contemporaneous high-cadence PTF survey of this region, which is useful for eliminating false-positives. Next year we plan to propose for a similar survey but at L and C bands, which will allow us to probe the phase space in terms of frequency.

COSMOS-2 is an EVLA survey starting in November 2012 which is characterized by unprecedented sensitivity at 3 GHz. Even though this survey will be only in one band, it will allow us to probe the phase space of transients in terms of timescales ranging from 1 day to 4 months, flux density greater than about 150μJy, and areal density greater than 10^{-3} deg^{-2}. As such, COSMOS-2 is a narrow-deep survey useful for finding faint transients (either intrinsically faint or due to large distance). Well matched multi-wavelength data exists for characterizing of the radio source population in COSMOS-2, as stated in §2. For this project, I will be developing a pipeline to find transients from raw COSMOS-2 data in near-real-time.

As part of the VLA-Archival project, we have analyzed all 200,000 images in the VLA archive in terms of source-finding. Our next step will be to find transients in this vast dataset. Finding transients over different fields of view, sensitivities and resolutions is going to be challenging. Finding optical counterparts will be possible for most fields through SDSS. From Figure 2 we see that this project is equivalent to a wide-shallow survey. The 7σ sensitivity would be about 2 mJy, and transients having an areal density greater than 10^{-4} can be probed. The cadence will be variable, but it gives us access to all the frequencies at which the VLA is capable of observing (albeit a much lesser bandwidth compared to the refurbished array).

The EVLA-Fast project will be contemporaneous to the COSMOS-2 project. The unique feature of this project is that it will probe transient (and variable) phenomena on timescales of seconds to hours, which is practically unexplored thus far. The plan is the same as mentioned in §2.

The EVLA-Calib project relies on using the EVLA archival images of the fields of 3C286 and other calibrators, observed roughly once every day. Considering the fact that observations with the refurbished array (EVLA) started in March 2010, a considerable amount of calibrator images will exist by the summer of 2013. In Figure 2, this project will probe similar part of the logN-logS space as the Stripe-82 project. However, unlike the latter, this project would correspond to a narrow-deep survey useful for probing larger distances (redshifts). There are a couple of challenges involved in doing this project: (i) achieving the desired rms (thermal limit of the data) implies that we need to achieve a dynamic ratio of better than 10^5, and (ii) finding multi-wavelength counterparts to the transients found, especially those at low flux densities ($\sim$0.3 mJy).

4. WHAT TO EXPECT OUT OF THIS STUDY

4.1. *Expected Science Yield*

While the 1.4 GHz radio sky is quiet, it might be favorable for finding electromagnetic counterparts to gravitational-wave sources. On the other hand, expected areal densities suggest that the possibility of finding variables and transients at higher GHz frequencies is greater.

We can already predict the number of variables that we might find at GHz frequencies. Integrating the differential source counts in Figure 2, we can estimate that the number of persistent radio sources above 100 μJy to be 910 deg^{-2} at 1.4 GHz (the value at 5 GHz is $\sim$200 lower). Taking into account the fact that 1% of the sources are variable at 1.4 GHz and upto 30% at 5 GHz, we estimate the fraction of strong variables, on a wide range of timescales, as 10 and $\sim$100 respectively per square degree.

Supernovae, non-thermal tidal disruption events (TDEs), stellar flares, orphan long-duration Gamma Ray Bursts Afterglows (OGRBAs) and neutron star (NS-NS) coalescence events are among the transients that we expect to see. Such detections will have large impact on several key questions such as the rate of TDEs, obscured supernovae, the beaming factor of GRBs and the rate of NS-NS mergers. Especially with the COSMOS-2 and VLA-Archival projects, we have the ability to go deep/wide so as to be able to detect several tens of OGRBAs as well as NS mergers. This is quite fascinating considering facilities such as aLIGO, which will be coming up in the near future for detecting GWs from such events.

The surveys carried out as part of the PhD thesis are comparable in sensitivity to those planned for next-generation facilities such as WSRT/Apertif, ASKAP and MeerKAT. Since large amount of data will be coming out of these SKA pathfinders, most of the reduction and analysis will have to be automated. This study will give the SKA pathfinders a census of variables and transients at GHz frequencies, and inform them about effective, well-tested procedures (eg. reliable searches for transients in radio images and the use of multi-wavelength data) to systematically explore the dynamic radio sky. Thus, our projects are forerunners of the most ambitious radio surveys of the future.

Lastly, the datasets which will be generated from our surveys will serve the astronomy community in terms of rich data for future research.

4.2. *Timeline and Expected Publications*

Fall 2012 - Winter 2013: (i) Work on the remaining analysis for the Stripe-82 S-band survey and submit the paper. (ii) Understand and improve on the EVLA real-time data-reduction pipeline and apply it to COSMOS-2 data. (iii) Start working on the EVLA-Fast project.
Summer 2013: (i) Apply for EVLA observing time for Stripe-82 surveys in L and C bands. (ii) Write and publish paper on VLA-Archival. (iii) Start working on EVLA-Calib project.
Fall 2013 - Winter 2014: (i) Write and publish papers on COSMOS-2 and EVLA-Fast.
(ii) Start working on Stripe-82-L/C if proposal is approved.
(iii) Apply for jobs, begin compiling thesis.
Summer 2014 - Fall 2015: (i) Write and publish paper(s) on Stripe-82-L/C (if applicable). (ii) Finish and defend thesis, graduate after a total of about 5 years with at least 5 first-author publications.

APPENDIX

Given a total observing time T, we can either do a wide-shallow or a narrow-deep survey, where wide/narrow refers to the area covered, and shallow/deep refers to the sensitivity in terms of limiting flux density. To find which of these will explore the largest volume, consider two surveys, one which observes a single pointing for time T, and the other which observes N pointings with time N/T alloted for each pointing. We know that the limiting flux density (S_0), integration time (τ), maximum distance (d_0) and the total volume (V_0) probed by a survey are related as:

$$S_0 \propto \frac{1}{\sqrt{\tau}} \propto \frac{1}{d_0^2} \Rightarrow V_0 \propto d^3 \propto \tau^{3/4} \tag{1}$$

$$\therefore \frac{V_1}{V_2} = \frac{T^{3/4}}{N \times (T/N)^{3/4}} = \frac{1}{N^{1/4}} \tag{2}$$

Thus we see that the volume probed by a wide-shallow survey (V_2) is larger than that seen by a narrow-deep survey (V_1) by a factor of the number of pointings to the power of 1/4. However, note that since the distance probed in these two kinds of surveys goes as $d_1/d_2 = \sqrt{N}$. This means that if we want to probe transient populations concentrated at large distances (redshifts), it is best to do a narrow-deep survey.

K.M. would like to thank Assaf Horesh, Stephen Bourke and Eran Ofek for useful discussions.

REFERENCES

Aller, M. F., Aller, H. D., & Hughes, P. A. 1992, ApJ, 399, 16
Archibald, A. M., et al. 2009, Science, 324, 1411
Arshakian, T. G., León-Tavares, J., Lobanov, A. P., Chavushyan, V. H., Shapovalova, A. I., Burenkov, A. N., & Zensus, J. A. 2010, MNRAS, 401, 1231
Becker, R. H., Helfand, D. J., White, R. L., & Proctor, D. D. 2010, AJ, 140, 157
Berger, E., et al. 2001, Nature, 410, 338
Bower, G. C., Saul, D., Bloom, J. S., Bolatto, A., Filippenko, A. V., Foley, R. J., & Perley, D. 2007, ApJ, 666, 346
Brunthaler, A., Menten, K. M., Reid, M. J., Henkel, C., Bower, G. C., & Falcke, H. 2009, A&A, 499, L17
Cameron, P. B., et al. 2005, Nature, 434, 1112
Camilo, F., Ransom, S. M., Halpern, J. P., Reynolds, J., Helfand, D. J., Zimmerman, N., & Sarkissian, J. 2006, Nature, 442, 892
Carilli, C. L., Ivison, R. J., & Frail, D. A. 2003, ApJ, 590, 192
Cenko, S. B., et al. 2012, ApJ, 753, 77
Cognard, I., Shrauner, J. A., Taylor, J. H., & Thorsett, S. E. 1996, ApJ, 457, L81
Condon, J. J. 1984, ApJ, 287, 461
Condon, J. J. 2007, in Astronomical Society of the Pacific Conference Series, Vol. 380, Deepest Astronomical Surveys, ed. J. Afonso, H. C. Ferguson, B. Mobasher, & R. Norris, 189
Cordes, J. 2007, in From Planets to Dark Energy: the Modern Radio Universe
Cordes, J. M., Lazio, T. J. W., & McLaughlin, M. A. 2004, New Astronomy Reviews, 48, 1459
de Zotti, G., Massardi, M., Negrello, M., & Wall, J. 2010, A&A Rev., 18, 1
Falcke, H., & Biermann, P. L. 1999, A&A, 342, 49
Fender, R. P., & Bell, M. E. 2011, Bulletin of the Astronomical Society of India, 39, 315
Fiedler, R. L., Dennison, B., Johnston, K. J., & Hewish, A. 1987, Nature, 326, 675
Fox, D. B., et al. 2005, Nature, 437, 845
Frail, D. A., Kulkarni, S. R., Berger, E., & Wieringa, M. H. 2003, AJ, 125, 2299
Frail, D. A., Kulkarni, S. R., Ofek, E. O., Bower, G. C., & Nakar, E. 2012, ApJ, 747, 70
Frail, D. A., Waxman, E., & Kulkarni, S. R. 2000, ApJ, 537, 191
Gaensler, B. M., & Hunstead, R. W. 2000, Publications Astronomical Society of Australia, 17, 72
Gaensler, B. M., et al. 2005, Nature, 434, 1104
Gal-Yam, A., et al. 2006, ApJ, 639, 331
Güdel, M. 2002, ARA&A, 40, 217
Hallinan, G., et al. 2007, ApJ, 663, L25
Hankins, T. H., Kern, J. S., Weatherall, J. C., & Eilek, J. A. 2003, Nature, 422, 141
Hjellming, R. M., et al. 2000, ApJ, 544, 977
Hodge, J. A., Becker, R. H., White, R. L., Richards, G. T., & Zeimann, G. R. 2011, AJ, 142, 3
Hyman, S. D., Lazio, T. J. W., Kassim, N. E., Ray, P. S., Markwardt, C. B., & Yusef-Zadeh, F. 2005, Nature, 434, 50
Hyman, S. D., Wijnands, R., Lazio, T. J. W., Pal, S., Starling, R., Kassim, N. E., & Ray, P. S. 2009, ApJ, 696, 280
Jackson, P. D., Kundu, M. R., & White, S. M. 1989, A&A, 210, 284
Karuppusamy, R., Stappers, B. W., & van Straten, W. 2010, A&A, 515, A36
Koopmans, L. V. E., et al. 2003, ApJ, 595, 712
Körding, E., Rupen, M., Knigge, C., Fender, R., Dhawan, V., Templeton, M., & Muxlow, T. 2008, Science, 320, 1318
Lazio, T. J. W., Ojha, R., Fey, A. L., Kedziora-Chudczer, L., Cordes, J. M., Jauncey, D. L., & Lovell, J. E. J. 2008, ApJ, 672, 115
Levinson, A., Ofek, E. O., Waxman, E., & Gal-Yam, A. 2002, ApJ, 576, 923
Lo, K. K., et al. 2012, MNRAS, 421, 3316
Lorimer, D. R., Bailes, M., McLaughlin, M. A., Narkevic, D. J., & Crawford, F. 2007, Science, 318, 777
Lovell, J. E. J., et al. 2008, ApJ, 689, 108
Marscher, A. P., & Gear, W. K. 1985, ApJ, 298, 114
Marscher, A. P., Jorstad, S. G., Gómez, J.-L., Aller, M. F., Teräsranta, H., Lister, M. L., & Stirling, A. M. 2002, Nature, 417, 625
Massi, M., Menten, K., & Neidhöfer, J. 2002, A&A, 382, 152
McLaughlin, M. A., et al. 2006, Nature, 439, 817
Miller-Jones, J. C. A., Rupen, M. P., Türler, M., Lindfors, E. J., Blundell, K. M., & Pooley, G. G. 2009, MNRAS, 394, 309
Mooley, K., Frail, D. A., Ofek, E., Miller, N., & Kulkarni, S. R. 2012, ApJ
Ofek, E. O., Frail, D. A., Breslauer, B., Kulkarni, S. R., Chandra, P., Gal-Yam, A., Kasliwal, M. M., & Gehrels, N. 2011, ApJ, 740, 65
Osten, R. A., & Bastian, T. S. 2008, ApJ, 674, 1078
Padovani, P., Miller, N., Kellermann, K. I., Mainieri, V., Rosati, P., & Tozzi, P. 2011, ApJ, 740, 20
Richards, M. T., Waltman, E. B., Ghigo, F. D., & Richards, D. S. P. 2003, ApJS, 147, 337
Sadler, E. M., et al. 2006, MNRAS, 371, 898
Seymour, N., et al. 2008, MNRAS, 386, 1695
Smolčić, V., et al. 2008, ApJS, 177, 14
Soderberg, A. M., et al. 2010, Nature, 463, 513
Trigilio, C., Leto, P., Leone, F., Umana, G., & Buemi, C. 2000, A&A, 362, 281
White, R. L., Becker, R. H., Helfand, D. J., & Gregg, M. D. 1997, ApJ, 475, 479
White, S. M., Pallavicini, R., & Kundu, M. R. 1992, A&A, 259, 149
Zauderer, B. A., et al. 2011, Nature, 476, 425