The Dynamic Radio Sky

Gregg Hallinan: Caltech

On behalf of the Caltech-NRAO Stripe 82 Survey (CNSS) collaboration

The Dynamic Radio Sky from Caltech

New all-sky imaging array below 100 MHz – Owens Valley LWA

Blazar monitoring program with 40m – Readhead et al.

Jansky VLA follow-up program (Horesh & Kulkarni)

Synoptic surveys with Jansky VLA (Hallinan and Kulkarni groups)
• Synoptic surveys have revolutionized transient science in optical, X-ray and γ-ray bands

• Key deliverables with additional serendipitous science

• BATSE, Swift, Fermi -> GRBs

• PTF, Pan-STARRS, LSST -> supernovae

*Synoptic radio transient surveys lag optical and higher energy surveys by at least a decade*
Case Study – 1979C

Supernova in M100 at 17 Mpc

Peak optical mag: ~12.2

Peak radio flux: ~10 mJy


Costa et al. (1997), van Paradijs et al. (1997)

Interstellar scintillation → angular size

Highly collimated outflow → provided reliable calorimetry of the explosion

Only radio observations provided reliable calorimetry of the explosion
Only synoptic surveys can fully characterize the radio transient sky

- **Hidden Explosions: Radio Supernovae, GRBs, NS-mergers**

- Half of supernovae remain undetected in the traditional optical searches, largely due to extinction via dust obscuration - radio observations can probe through dust for Type Ib, Ic and type II SNe

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- Relativistic outflows associated with GRBs are highly collimated - the typical opening angle of the collimated jet is poorly constrained

- Radio observations of “orphan afterglows” can provide an unbiased measure of the true rate - Frail et al. 1997, 2012, Gal-Yam et al. 2006

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- Advanced LIGO (aLIGO) and Advanced Virgo (AdV) commence in 2015 - binary neutron star (BNS) coalescence the most likely source detected

- Late time radio afterglows of NS-mergers are isotropic – detectable with the VLA (Nakar & Piran 2011)
- Pulsing source (period 77 mins) discovered in archival 330 MHz VLA data (Hyman et al. 2007)

- Optically obscured supernovae discovered in NGC 4216 through comparison of FIRST and NVSS (Levinson et al. 2002, Gal-Yam et al. 2006)

• Some success from blind transient searches...
New Radio Transient Machines

Jansky VLA: 10x sensitivity – Upgrade complete!

ASKAP: Under construction

MeerKAT: Under construction

Apertif: Upgrade underway
Dedicated VLA radio transient survey of SDSS Stripe 82 spanning 3 years

Stripe 82 – a 270 sq. deg. region on the celestial equator with a wealth of multi-frequency legacy data

Observing frequency of 2-4 GHz

Pilot Survey:

Program ID: 12A-371 – 50 hours (PI Kulkarni)

Full survey:

Program ID: 13B-370 – 3 epochs spaced over 6 weeks (PI Hallinan)

Program ID: 15A-421 – 2 epochs spaced over 2 months (Hallinan et al. 2015)

Final combined survey – 270 sq. deg. to ~35 μJy
CNSS Timeline

Mooley et al. 2015

Jul 13 - Aug 24 CNSS 50 Sq. Deg. Pilot

Dec 18 - Feb 17 Full CNSS Epochs 1-3

Feb 20 - May 10 Full CNSS Epochs 4-5
Pilot Survey (Mooley et al. 2015)

- 3 epochs (RMS ~ 70 microJy), each with ~1000 pointings of 39 seconds carried out in 2x7 hour blocks, with 2 GHz bandwidth (2-4 GHz) in 1000 channels 0 500 GB of visibility data

- Every pointing for each epoch was at the same telescope elevation and azimuth

- RFI removal, calibration, imaging (1000 x 2K x 2K), source extraction and transient detection completed within ~3 hours to trigger follow-up (VLA, Palomar, Keck, Swift)

- How -> Stephen Bourke’s AIPSLite package (Bourke et al. 2013) and Kunal Mooley’s source extraction (sfind-based) and transient detection pipeline(Mooley et al. 2015)
Pilot Survey (Mooley et al. 2015)

- Most transients coincident with faint extragalactic counterparts – background haze of AGN

- Two transients coincident with a very bright optical counterparts...
- Transient coincident with a very bright star: r ~ 10
- K type subgiant at 220 pc – likely RS CVn
Full CNSS Survey

- Dynamically scheduled

Required commissioning of on-the-fly mapping (OTF)

Managed by K. Mooley (Epochs 1-3) and M. Anderson (Epochs 4-5)
9 degrees!

0.8 Gpix image from a single observing block

Cutouts compiled by S. Myers
CNSS Epochs 1-3 vs FIRST

- CNSS epochs 1-3 too closely spaced to meaningfully probe extragalactic transient population

- Can combine epochs and use FIRST as a reference image – similar resolution

- Combined CNSS epochs 1-3 -> rms noise ~50 μJy -> 7,000 sources > 0.5 mJy

Only 384/7000 without a FIRST counterpart
- Synchrotron self-absorbed
- Sidelobes
- Gaps in FIRST coverage

- Compared with SDSS BOSS catalog and Catalog of the Local Universe (CLU) (M. Kasliwal) – 14,000 galaxies (~30% completeness)

- Searched a projected radius of 30 kpc around each galaxy (18 degrees total)

- 33 sources shortlisted -28 were extended sources, imaging artifacts or too far from the galaxy

- 1 was an M dwarf flare

- Follow up on 4 sources with VLA

- Two were nuclear transients, two were not...

Berger 2014
CNSS Transients

Intense verification process underway

VLA follow-up reveals slow variability over 1 year

Deep Keck K band imaging for background AGN – no detection

VLBA observations being reduced
VLA Sky Survey

- 3 epochs, each covering ~30,000 sq. deg. with 36 months between epochs
- Partly motivated by progress with CNSS
- VLASS will be the first synoptic radio survey to detect large samples of explosive transients
- Slow evolution timescale - 3 VLASS epochs spaced by 36 months to maximize detection rate
- Choice of frequency and resolution key advantage to VLASS
  - Faster evolution timescale at S band relative to L band
  - Resolution of ~3” key to localizing events; e.g. distinguishing GRBs/SNe/BNS-mergers from AGN activity
- VLA 1-40 GHz follow-up key advantage to VLASS
- Detection rates for VLASS are comparable to SKA pathfinders
- Very strong synergy with ZTF, CLU and ALIGO
Summary

• Upgrades to existing telescopes and a new generation of interferometers are opening up parameter space in the transient radio sky.

• The VLA is particularly noticeable in this regard, having already completed a substantial upgrade allowing systematic searches for both galactic and extragalactic transient populations with a reasonable allocation of time.

• We have used the VLA to carry out the Caltech-NRAO Stripe 82 Survey (CNSS) involving a 3-epoch pilot survey and a 5 epoch full survey spanning 18 months.

• One of the most exciting populations uncovered are extragalactic explosive events with luminosity exceeding that expected for late time supernovae afterglows.

• Two such events have been discovered and are undergoing intensive verification and follow-up.