

Chapter 2 Synergies and Techniques

2.1 The ngVLA and the DSA2000

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Summary

The next Generation Very Large Array will replace the existing VLA and VLBA with a revolutionary facility with 10x higher sensitivity, covering 1 GHz to 116 GHz, achieving a resolution as high as 60 μ as, and a brightness temperature sensitivity of a few K at mas resolution. The ngVLA will be the primary radio facility for determining the physical processes driving transient, and other, cosmic phenomena discovered with the DSA2000 surveys, through high resolution, broad-band follow-up.

The next generation Very Large Array consists of 244 x 18m off-axis parabolic antennas distributed across the USA and Mexico (Selina & Murphy ngVLA memo 17, 2017). The array operates from 1 GHz to 116 GHz with a maximum bandwidth of ~ 20 GHz. The configuration has a Core of 114 antennas semi-randomly (inverse radially weighted density), extending to baselines of 4 km, centered at the current VLA site. From there, a 5 arm exponential Spiral of 54 antennas extends to baselines of 40 km. Beyond that are 30 Mid antennas, also in a 5 arm spiral extending into Mexico, to baselines of 1000 km. Lastly, the 30 LONG antennas are situated in 10 stations distributed from Hawaii to Puerto Rico, for baselines of 9000 km (Carilli et al. ngVLA memo 92). There is also a small, close-packed array of 19 x 6 m antennas, with maximum baseline of 60 m.

Figure 1 shows two axes of parameter space for the ngVLA relative to existing, and other future, facilities: sensitivity ($\text{area}/T_{\text{sys}}$), and resolution. The ngVLA will have an order of magnitude better sensitivity than existing arrays operating in its frequency range. The ngVLA will also afford superb resolution: down to 60 μ as at 115 GHz. Coupled with the high frequency capabilities of ALMA 2030, operating up to almost 1 THz, and the low frequency capabilities of the SKA, operating down to at least 50 MHz, these facilities represent a powerful suite of telescopes to study cosmic phenomena into the mid-century.

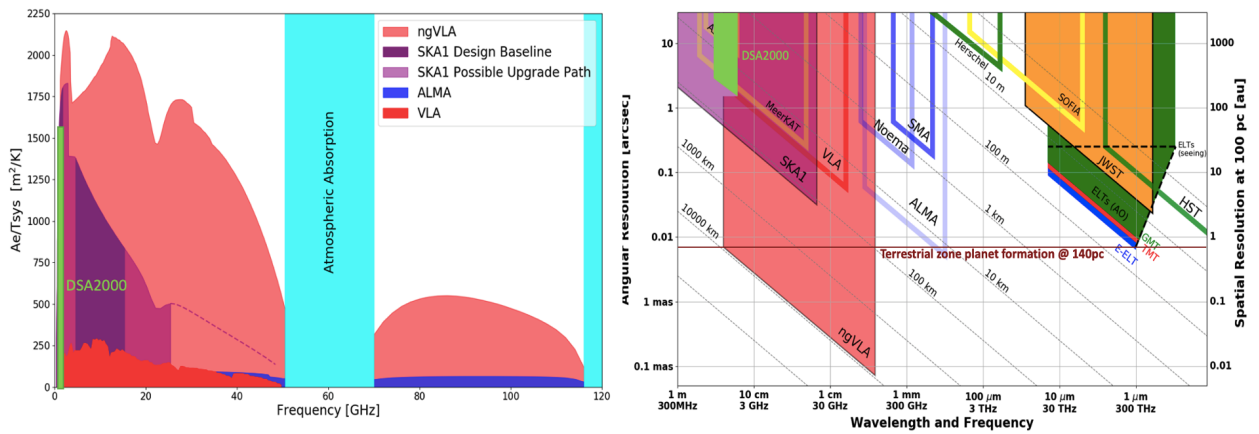


Figure 2.1: Parameter space of radio and other wavelength facilities into the mid-century. Left: Sensitivity. Right: Angular resolution

However, all of these facilities are limited in one respect: field of view (FoV). The ngVLA is primarily designed as a PI-proposal driven, 'point and shoot' facility for detailed studies of specific targets. FoV is the parameter in which the DSA2000 really stands-out. The DSA2000 has an order of magnitude, or more, larger FoV than the ngVLA and SKA-mid. Coupled with its competitive sensitivity (Fig 1), and full polarization response, the DSA2000 represents the ideal array for synoptic wide-field surveys, with the potential to discover myriad

new cosmic phenomena at low flux densities, down to millisecond timescales. However, simply obtaining a flux density at ~ 1 GHz is of limited information content. To characterize the discovered sources, and determine the physical processes driving new phenomena, broad-band, high resolution follow-up observations are required. That is where the ngVLA will play a key role.

The astronomical community has identified five key science goals for the ngVLA (see ngVLA memo 19):

- Unveiling the Formation of Solar System Analogues on Terrestrial Scales
- Probing the Initial Conditions for Planetary Systems and Life with Astrochemistry
- Charting the Assembly, Structure, and Evolution of Galaxies Over Cosmic Time
- Using Pulsars in the Galactic Center as Fundamental Tests of Gravity
- Understanding the Formation and Evolution of Stellar and Supermassive BH's in the Era of Multi-Messenger Astronomy

We briefly highlight a few of the obvious synergistic science programs that could be realized with combined DSA2000 surveys and ngVLA follow-up, starting with an important remind of the power of such follow-up to understand new physical phenomena.

The LIGO discovery of the first gravitational wave source, GW170817, opened a new window on the Universe, revealing gravitational radiation from merging $\sim 30 M_{\odot}$ black holes (Abbott et al. PRL, 119, 161101). The follow-up identification of the electromagnetic counterpart was remarkably fast in the radio and the optical, isolating the source to a galaxy at 41 Mpc distance (Abbott et al. 2017, ApJL, 848, L12; Hjorth et al. 2017, ApJL, 848, L31; Hallinan et al. 2017, Science, 358, 1579). Broad-band radio monitoring found a turn-over in the radio light curve about 150 days after the merger, while mas-resolution imaging with the VLBA detected superluminal motion of the radio source. These radio observations provided the basis for a physical model in which the electromagnetic radiation arises from the formation of a relativistic jet during the merger, which expands initially through the circum-binary debris, and then emerges into the interstellar medium (Dobie et al. 2018; Mooley et al. 2018).

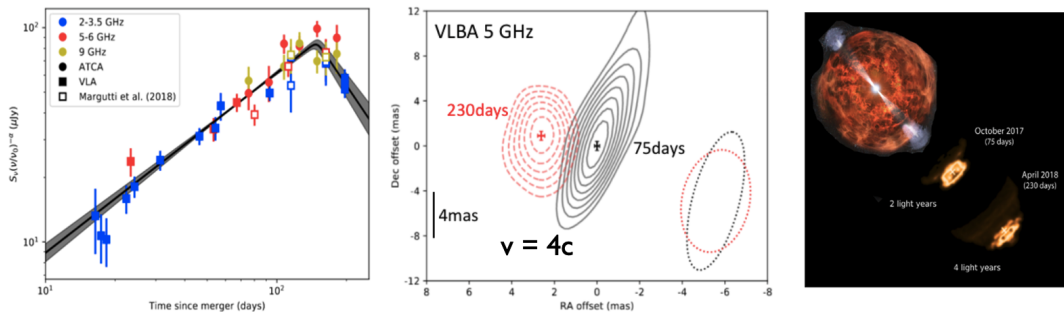


Figure 2.2: Left: Radio light curve of the first gravitational wave source, GW170817. Center: VLBA images showing the super-luminal motion. Right: schematic of the 'smothered, emerging relativistic jet' model formed by the merging $30 M_{\odot}$ black holes (Dobie et al. 2018, ApJ 858, L15; Mooley et al. 2018, Nature, 561, 355).

The case of GW170817 accentuates the fact that, while the discovery of new phenomena may occur through wide field surveys, understanding the physics of these sources requires high resolution, multi-band follow-up. The DSA2000 expects to target 10 to 20 LIGO events per year for EM identification. The ngVLA is well poised to perform the broad band, high resolution follow-up, from 1 GHz to 116 GHz, again down to $60 \mu\text{as}$ resolution.

The discovery of thousands of exo-planets, hundreds in the 'habitable zone,' has spurred renewed interest in the possibility of life outside the Solar system. Primary science drivers for the ngVLA include probing deep into proto-planetary dusty disks with sub-AU scale imaging of planet formation, potentially down to a few Earth

masses, as well as the study of the pre-biotic molecules that provide the chemical initial conditions in forming planetary systems (McGuire et al. 2018, ASP, 7, 217 and 245; Ricci et al. 2018, ASP, 7, 147). The ngVLA will make 'movies' of planet formation, showing the differential rotation of rings and gaps in dusty disks on sub-AU scales, as well as dust traps, and potentially even accretion onto the planets themselves (Fig. 3; ngVLA memos 6, 57, 68, 101).

In terms of end-of-life stellar evolution and enrichment of the ISM, the ngVLA will also provide exquisite movies of the 'boiling' of stellar atmospheres in evolved massive stars (AGB and Red Supergiants), corresponding to the dominant events enriching the ISM with heavy elements (Fig. 3; ngVLA 66, 95).

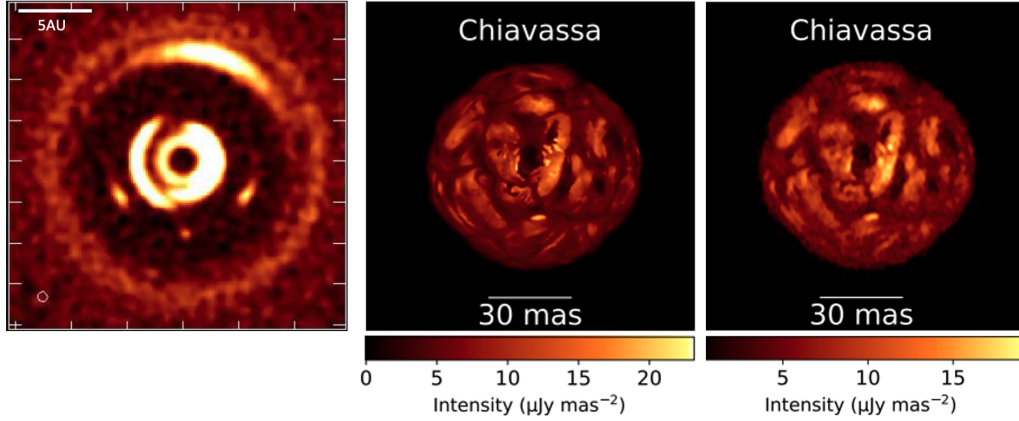


Figure 2.3: Left: Simulation of a forming Jupiter (lower dot), in a $0.1 M_{\odot}$ proto-planetary disk around a $1 M_{\odot}$, 1 Myr old proto-star (Harter et al. 2019, ngVLA memo 68), at 100 GHz, 7 mas resolution (1 AU at 140 pc). Center and right: model and ngVLA simulated image for the 46 GHz photosphere ($\tau = 1$) of a red supergiant star at 220 pc, during its major, end-of-life mass-loss phase (Akiyama & Mathews 2019, ngVLA memo 66, Petretti et al. 2021, ngVLA memo 95), at 5 mas resolution

Where does the DSA2000 fit into the hunt for habitable worlds? Answer: through determining the inhabitability of planets. The majority of terrestrial planets in the habitable zone will be found associated with M dwarf stars, simply because M dwarfs are the most common star. However, it is now well documented that M-dwarfs are extremely magnetically active, including strong millimeter flares, and auroral emission associated with large scale stellar dipole fields of a few thousand Gauss (eg. Howard et al. 2022, ApJ, 938, 103; Bastian et al. 2022, ApJ, 935, 99). Such extreme 'exospace weather' will have severe deleterious effects on planetary atmospheres, and the subsequent development of life, through strong magnetospheric interactions. The DSA2000 will provide the first true census of M dwarf radio activity, with the expectation of identifying 10^6 flare events, 10^5 stars through non-thermal coronal emission, and 10^3 stars in thermal coronal emission. Determining the prevalence of extreme exospace weather has become a key term in the Drake equation, and hence in understanding the probability for the development of life outside the Solar system.

Another key science goal of the ngVLA is a precision measurement of the dense gas history of the Universe through observation of low order rotational transitions of CO back to within ~ 1 Gyr of the Big Bang (Decarli et al. 2018, ASP 7, 565). Molecular gas is the direct fuel for star formation in galaxies. Current surveys suggest a parallel rise and fall for the cosmic molecular gas density as is seen in the star formation rate history, although the errors are substantial (Walter et al. 2020, ApJ, 902, 111). The goal of the ngVLA is to provide an order of magnitude improvement in the measurement of the molecular gas content of galaxies back to cosmic reionization.

Where does the DSA2000 fit into the study of the history of baryons in galaxies? Answer: through the

identification of $\sim 5 \times 10^6$ galaxies in HI 21cm emission out to $z \sim 1$ (or perhaps $z \sim 1.8$, if extended to 0.5 GHz). While not probing the earliest cosmic epochs, this redshift range does reach toward the peak epoch of cosmic star formation rate density ('cosmic high noon'), and in particular, covers the redshift range over which the cosmic star formation rate density declines by an order of magnitude – the epoch of 'cosmic demise'. The current constraints on the HI density over this time range are poor. Knowledge of the HI density evolution is crucial for understanding late-time accretion of gas onto galaxies from the IGM, to address the question: why is the star formation rate declining so dramatically to the current epoch (Walter et al. 2020)?

These are just a few of the obvious science synergies between the DSA2000 surveys and the ngVLA deep, high resolution follow-up. However, there remains one open issue: timing. The DSA2000 is expected to start full operations toward the end of 2026. The current ngVLA timeline has early science (defined as when the ngVLA capabilities exceed those of the current VLA and VLBA), beginning in late 2028, with steady increase in capabilities until full operations sometime in the middle of the next decade. Hence, for the first two or three years of DSA2000 operations, source radio follow-up will still rely on the VLA and VLBA.

2.2 Synergies with SPHEREx

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Summary

SPHEREx, the upcoming NASA MIDEX mission to be launched in 2025, will spectro-image the near-infrared all-sky at 6.2'' spatial resolution in 102 wavelength channels over 0.75–5 μ m. This is comparable to DSA-2000 in terms of sky coverage, angular resolution and timeline, and we anticipate rich synergies between the two. We outline some synergy examples such as providing redshift verification and transient counterparts, as well as cross-correlation potentials for weak gravitational lensing and extragalactic background light decomposition that warrant further investigations.

State of the Field

SPHEREx¹ will generate the first all-sky spectroscopic survey in the near-infrared over 0.75 – 5 μ m in 102 wavelength channels with a 6.2'' spatial pixel, with a 5 σ point source sensitivity better than AB magnitude $M_{AB} > 19$ per wavelength channel (Doré et al. 2014). During its nominal two-year mission lifetime, SPHEREx will survey the full sky four times, with frequent visits to the two deep fields near the north and south ecliptic poles, each about 100 deg² in size. From its low earth orbit SPHEREx will observe part of the deep fields every 86 minutes in a few colors, making the deep fields particularly synergistic for transient sciences when both DSA-2000 and SPHEREx are in operation.

SPHEREx will produce a rich dataset. In addition to providing 3D spectral images, SPHEREx is expected to measure the spectra of over one billion galaxies – 10 millions of which will have a redshift accuracy $\Delta z/z < 3\%$ and more than 100 millions galaxies a redshift accuracy of $\Delta z/z < 10\%$. There will be 25,000 galaxy clusters, more than 100 million main sequence stars, more than 400 brown dwarfs, over one million Quasars and potentially 3-300 $z > 7$ Quasars, to name a few discovery potentials (Doré et al. 2016). The data and catalogs will be released to the public at a fast pace: the spectral-image data that can be particular useful for transient sciences will be released two months after observation, and the source catalog will be released 8 months after the completion of the third all-sky survey. All these will enable rich synergistic multi-wavelength studies (Doré et al. 2018).

DSA-2000's impact

The DSA-2000 HI survey will detect $\sim 5 \times 10^6$ galaxies out to $z = 1$ with exquisite redshift accuracy. This unique dataset, in addition to mapping the neutral hydrogen distribution and evolution, has the potential to enhance the many sciences SPHEREx has to offer:

- (1) For example, these HI galaxies can be cross-matched to SPHEREx sources and help verify and sharpen their redshifts derived from SPHEREx alone, which could improve the accuracy of the non-gaussianity parameter f_{nl} determination through large-scale clustering measurement, shedding light on the physics of inflation in the very early Universe.*
- (2) Additionally, the HI galaxies are beacons of the underlying matter distribution, and can aid the redshift decomposition of the diffuse extragalactic background light measured by SPHEREx through tomographic cross-correlation (e.g., Cheng and Chang 2022). The large-scale clustering amplitude reveals the mean near-IR intensity associated with all sources of emission while the Poisson scale of such*

¹<https://spherex.caltech.edu>

a cross-correlation can further reveal the near-IR properties of HI-hosting galaxies, which would be particularly interesting. A cross-correlation forecast between the DSA-2000 HI sample at $z = 0.1 - 0.3$ and SPHEREx diffuse maps, following the formalism of Cheng and Chang 2022, indicates that both the clustering and Poisson amplitudes can be detected at high significance across wavelength. Figure 1 shows a rough estimate of signal-to-noise (SNR) for the cross-correlation between DSA-2000 HI galaxies and SPHEREx all-sky diffuse maps in the linear clustering (blue) and Poisson (orange) shot noise regimes, assuming for the purpose of this estimation 75% of HI sources reside between $z = 0.05 - 0.2$ with a uniform redshift distribution. These measurements would help improve our understanding of galaxy formation and evolution.

The DSA-2000 radio continuum sources will be of great interest in cosmology as well. Tomographic cross-correlation between radio sources and SPHEREx galaxies can reveal the redshift distribution dN/dz of radio sources through the redshift clustering technique (Newman 2008; Ménard et al. 2013), potentially out to high redshift. Furthermore, weak gravitational lensing, now an important observational technique for probing the growth and geometry of the universe, can be performed in cross-correlation using radio and near-infrared observations. This approach offers an effective mitigation of observational systematics that could otherwise bias the shear measurements, as systematics associated with each dataset are unlikely to correlate (e.g., Harrison et al. 2016; Camera et al. 2017; Harrison et al. 2020). As the SPHEREx point-spread-function is undersampled, it would be difficult to derive shape measurement from SPHEREx alone, however, tomographic galaxy-galaxy lensing, using radio as lensing sources and SPHEREx galaxies as lenses as a function redshift, can in principle bring rich information about galaxy astrophysics and cosmology (e.g., Demetroullas and Brown 2018).

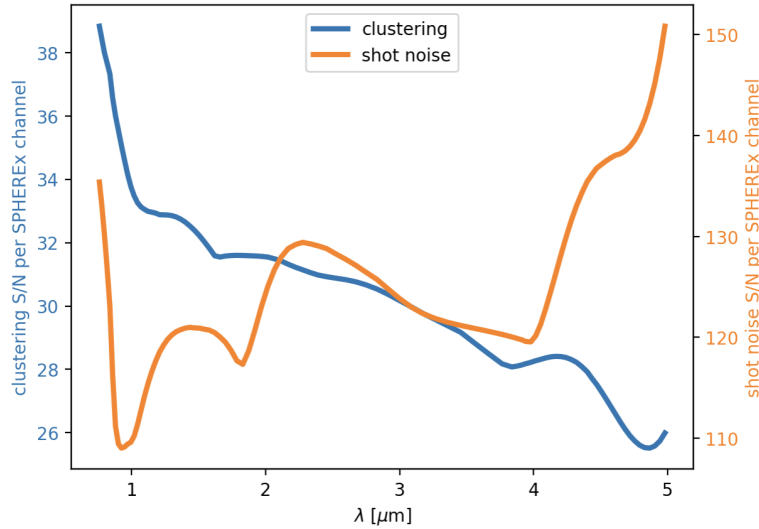


Figure 2.4: Expected signal-to-noise ratio (S/N) per SPHEREx wavelength channel between the DSA-2000 HI galaxies at $z = 0.1 - 0.3$ and the SPHEREx all-sky diffuse maps as a function of wavelength. The blue curve indicates the expected cross-power spectrum significance in the linear clustering regime, while the orange curve marks the S/N in the Poisson shot noise regime. Note both can be detected at high statistical significance.

2.3 Vera C. Rubin Observatory and DSA-2000: A winning synergy to unveil populations of elusive transients

Authors: Igor Andreoni

Summary

The Vera C. Rubin Observatory in the optical and DSA-2000 in the radio are new world-class survey instruments that will enable the systematic exploration of large sky volumes. Synergies between Rubin and DSA-2000 can be particularly valuable to discover populations of rare transients that provide us with unique insights about the physics of compact objects. These include electromagnetic counterparts to gravitational-waves, “orphan” gamma-ray burst afterglows, and relativistic tidal disruption events. Here, the potential of a Rubin & DSA-2000 synergy is demonstrated using the work done by current optical surveys such as the Zwicky Transient Facility, multi-wavelength follow-up telescopes, and with simulations.

State of the Field

Some slow radio transients are counterparts to elusive fast optical/infrared transients. Phenomena at their origin of these transients include binary neutron star mergers, gamma-ray bursts (GRBs) and other types of relativistic mass ejection such as jetted tidal disruption events (TDEs). **Neutron star mergers** (i.e., binary neutron star and neutron star–black hole mergers, under some conditions) can be accompanied by bright multi-wavelength transient emission (Abbott et al. 2017a). The optical/infrared counterpart, called “kilonova”, raises and fades within a few days (e.g., Andreoni et al. 2017; Arcavi et al. 2017b; Kasliwal et al. 2017a; Smartt et al. 2017) and is largely powered by the decay of newly synthesized r -process nuclei with high atomic number. A radio afterglow was also detected and has remained observable for years, explained by either a collimated ultrarelativistic jet (viewed off-axis) or a cocoon of mildly relativistic ejecta (e.g., Hallinan et al. 2017b). The optical kilonova associated with GW170817 was fainter, faster and reddened more quickly than typical supernovae. These properties and the intrinsic rarity of neutron star mergers in the nearby universe make kilonovae difficult to observe during regular operations of optical surveys and none has been found to date independently of gamma-ray or gravitational-wave triggers (e.g., Andreoni et al. 2021). A few dozen kilonovae (e.g., Andreoni et al. 2022b; Setzer et al. 2023) are expected to be found serendipitously by Vera C. Rubin Observatory LSST (Ivezić et al. 2019, located in Chile), which is coming online in 2025, thanks to its exceptional combination of wide field of view (9.6 deg^2) and depth ($r \sim 24.7 \text{ mag}$ in 30s exposure time). Rubin is expected to find a large number of other fast transient classes, including “**orphan**” **afterglows** for which the associated GRB went undetected, or where the Lorentz factor is too low ($\Gamma < \sim 100$) to produce a GRB in the so-called “dirty fireball” model (Paczynski 1998). Similarly to kilonovae, the optical emission from orphan afterglows can fade rapidly (but the evolution might be slower for off-axis GRBs) and is typically observable for only a few days. A radio afterglow, on the other hand, could remain bright for months or years. Systematic optical searches with the intermediate Palomar Transient Factory (iPTF) and Zwicky Transient Facility (ZTF; Bellm et al. 2019) surveys unveiled several afterglows without a detected GRB counterpart (Cenko et al. 2015; Ho et al. 2020; Andreoni et al. 2021; Ho et al. 2022a), but confident dirty fireball or off-axis GRB candidates still need to be found Ho et al. 2022a. A particularly exciting fast optical transient, named AT2022cmc, was recently discovered in ZTF data and was interpreted as the first **jetted TDE** found by an optical survey, in the form of a rapidly-fading transient (Andreoni et al. 2022a; Pasham et al. 2023). An exceptionally bright radio transient was found associated with

AT2022cmc (Andreoni et al. 2022a), whose monitoring also showed rapid day-scale variability around 16GHz (Rhodes et al. 2023). A large population of jetted TDEs could be found in the near future by X-ray, optical, and radio surveys.

In summary, many fast (hours to days) optical transients will be found by Rubin Observatory. Their identification will constitute a big data problem, given that up to 10 million alerts will be generated every night, each one indicating the detection of a variable or transient source. DSA-2000 is also expected to find ~ 1 billion sources, many of which will be transients that need optical photometric and/or spectroscopic data to be classified.

DSA-2000's impact

The DSA-2000 all sky survey will be able to observe the peak of a transient similar to the radio counterpart to GW170817 out to ~ 300 Mpc. An association between a DSA-2000 radio transient and a Rubin kilonova candidate will provide invaluable information about the nature of the transient and the astrophysics of the source. Combined optical + radio detection of orphan afterglows and jetted TDEs with Rubin and DSA-2000 will also serve as a strong diagnosis tool for the fast and slow transients discovered in Rubin and DSA-2000 data, respectively. A synergy between Rubin and DSA-2000 will enable the building of sizable samples of rare transients that are largely out of reach for current facilities. Tools may be developed to facilitate Rubin + DSA-2000 source cross-matching and combined data analysis.

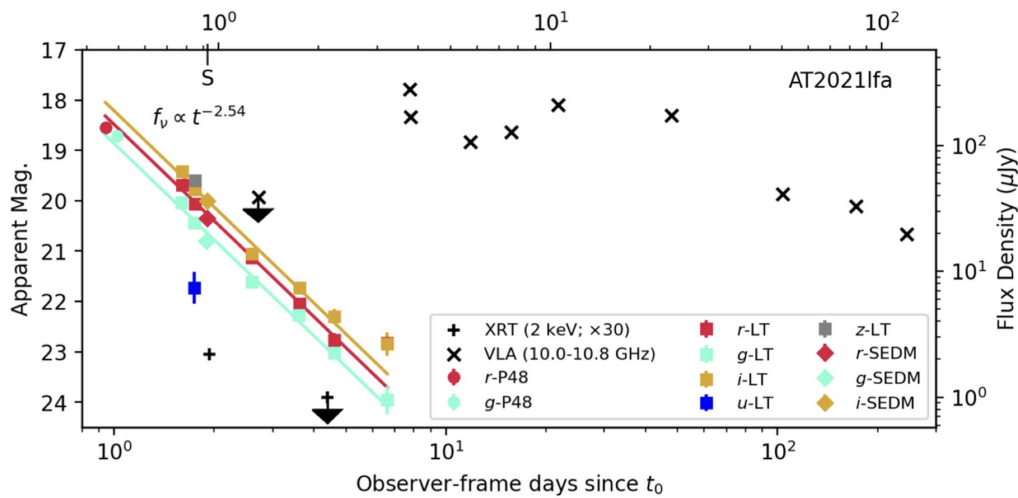


Figure 2.5: Example of a GRB afterglow that was identified as a rapidly evolving optical transient in Zwicky Transient Facility survey data (figure taken from Ho et al. 2022a). Follow-up observations revealed a slow transient counterpart at radio wavelengths. A synergy between Rubin and DSA-2000 will naturally yield many such elusive transients by providing valuable information for the transient classification and characterization.

System requirements / desired additions to baseline design (see table below)

The current DSA-2000 baseline plan will open a great discovery space in the radio. The Rubin strategy will likely be based on a “rolling cadence” approach, in which the sky coverage will not be homogeneous by season. The survey footprint will be divided in bands that will be imaged more or less frequently depending on the season to obtain some well-sampled light curves. Self-absorption in relativistic transients could be high and a significant time delay between a fast optical transient and its becoming observable in the DSA-2000 band could be present and taken into account. It would be preferred if the

DSA-2000 strategy takes into account when equatorial fields are surveyed by Rubin at higher cadence to maximize the detection of radio counterparts to fast optical transients.

Table 2.1: Project requirements compared to DSA-2000 baseline reference design

	DSA-2000 baseline reference design	match to project
Frequency band	0.7–2.0 GHz	higher frequencies would be less sensitive to self-absorption
Declinations	$\delta > -31^\circ$	low Decs could be prioritized if an inhomogeneous cadence is chosen
Cadence	1 every 4 months	suggestion 1: higher cadence on Rubin deep drilling fields; suggestion 2: take Rubin’s rolling cadence into account

2.4 Deconvolution & superresolution with POLISH

Authors: Liam Connor

Summary

DSA-2000 in a new interferometric imaging regime due to the lack of visibility data and its densely sampled aperture. The former point means we require image-plane deconvolution and the latter suggests we can be ambitious in our image reconstruction, e.g. achieving super-resolution. We built a learning-based imaging algorithm that can deconvolve radio interferometric data and recover angular scales below the diffraction limit. POLISH is residual neural network that has been trained on a large sample of image pairs (dirty image and true sky image) such that it can learn deconvolution^a. POLISH's super-resolution will enable several key science cases, but could still be significantly improved with a focused effort by a GPU programmer or AI expert.

^a<https://ui.adsabs.harvard.edu/abs/2022MNRAS.514.2614C/abstract>

State of the Field

CLEAN has been used for decades as the de facto standard deconvolution algorithm in radio interferometry. The Cotton-Schwab algorithm is one the most prominent variants of CLEAN. It relies on ungridded visibility data for its iterative approach, to which the DSA-2000 will not have offline access. CLEAN is typically not able to achieve super-resolution due to its use of a “restoring beam”, but also because the algorithm is inherently bad at recovering high spatial frequencies. Bayesian-inspired methods, such as Regularized Maximum Likelihood (RML) can achieve super-resolution, but are slow, require visibilities, and often have a human in the loop.

In the past five or so years, there have been tremendous advances by the computer vision community in applying learning-based methods to inverse problems. This is particularly true for super-resolution, where efficient neural network architectures have been found for recovering high spatial frequencies. With POLISH, we have chosen to capitalize and build on those advances.

DSA-2000's impact

POLISH was designed specifically for the DSA-2000, since no other algorithm was 1) fully automated without a human in the loop 2) image-plane only 3) able to achieve super-resolution and 4) feed-forward and fast. As it happens, POLISH has proven to be a generic deconvolution algorithm as it has been applied to real VLA data as well as optical data for direct imaging exoplanets. We have published on POLISH and its weak lensing application^a and we have made the code available^b.

^a<https://ui.adsabs.harvard.edu/abs/2022MNRAS.514.2614C/abstract>

^b<https://github.com/liamconnor/polish-pub.git>

System requirements / desired additions to baseline design

POLISH requires image plane data and a well-understood PSF. As long as both are available, a model can be trained for deconvolution and super-resolution.