VERY LARGE ARRAY SKY SURVEY

Eric J. Murphy, Caltech/IPAC

Galactic Center (Survey) Multiwavelength Image
Credit: X-ray: NASA/UMass/D.Wang et al., Radio: NRAO/AUI/NSF/NRL/N.Kassim, Mid-Infrared: MSX

The Karl G. Jansky Very Large Array

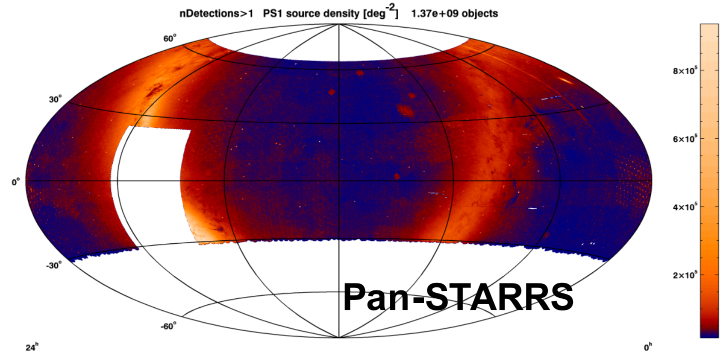
Reconfigurable array located in central New Mexico

- 27x25m antennas in the shape of a Y, can be in one of four configurations, D (most compact, B_{max}~1km) to A (most extended, B_{max}~36km)

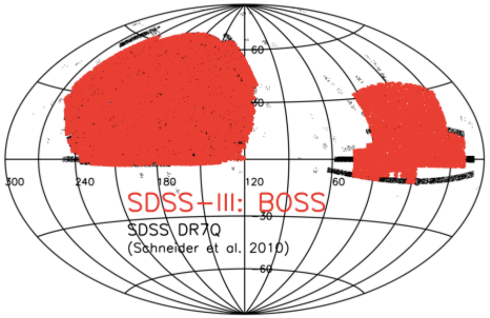
- Collecting area equivalent to a 130m aperture
- Field of view 45'/ν(GHz)
- Frequency range 350 MHz to 50 GHz
- Spatial resolution as high as 40mas (depends on ν and array configuration)

Surveys and the VLA

Why revisit this now?



- Science based on surveys comprise a steadily increasing fraction of VLA publications
- 20 years since NVSS and FIRST!



- New capabilities on the VLA
  - OTF mosaics, wide fractional bandwidths for increased continuum sensitivity, instantaneous spectral index determination, polarization
- New survey instruments being specifically designed for all-sky coverage, need radio counterpart *with comparable resolution*
- New scientific opportunities, especially in time domain

The VLA Sky Survey (VLASS) initiative

- In July 2013 NRAO announced that it would consider a new radio sky survey using the Karl G. Jansky VLA
  - https://science.nrao.edu/science/surveys/vlass
- Science and survey definition led by the community
- Open *international* participation, public data and products
- Fall 2013 call for White Papers on technical aspects and science goals issued: *22 received, 180 unique authors*
- Well-attended AAS workshop, January 2014
- 2014: Survey Science Group (SSG), working groups formed
  - survey proposal developed, drafts posted, comments, refined
  - technical implementation plan

Science Survey Group (SSG)

- Co-Chairs: **Eric Murphy (IPAC)** & **Stefi Baum (RIT, U. Manitoba)**

- Working Group Co-Chairs:
  - Programmatic: Jim Condon (NRAO), Rick White (STScI)
  - Extragalactic: Gordon Richards (Drexel), Jackie Hodge (NRAO)
  - Galactic*: Rachel Osten (STScI), Joe Lazio (JPL), Cornelia Lang(U Iowa)
  - Transients: Gregg Hallinan (Caltech), Ashley Zauderer (CfA)
  - Technical: Casey Law (UC Berkeley), Steve Myers (NRAO)
  - Outreach: Susana Deustua (STScI), Nicole Gugliucci (SIUE/CosmoQuest)

- At-Large Councilors:
  - Niel Brandt (Penn State), Jim Cordes (Cornell), Mark Dickinson (NOAO), Tracey Clarke (NRL), Sui Ann Mao (MPIA), Michael Strauss (Princeton)

- A few notable non-SSG heavy hitters include:
  - Michael Brown, Shami Chatterjee, Laura Chomiuk, Ian Heywood, Matt Jarvis, Mark Lacy, Tom Maccarone, Betsy Mills, Kunal Mooley, Larry Rudnick, Greg Sivakoff, Lorant Sjouwerman, Russ Taylor

A Significant Community Effort

VLASS Headline Science Themes

- Imaging Galaxies Through Time and Space: (talk by Lacy)

  Following the Ecology of Galaxies, Star Formation, and their Black Hole Engines.

- Radio Sources as Cosmological Probes: (talk by Jarvis)

  Tracing the Underlying Dark Matter Density Field.

- Hidden Explosions: (talk by Hallinan)

  Unbiased Measurements of Energetic Events.

- Faraday Tomography of the Magnetic Sky: (talk by Rudnick)

  Charting the Emergence of Large-Scale Magnetic Fields in Galaxies

- Peering Through Our Dusty Galaxy: (talk by Chatterjee)

  Finding and Studying Active Stars and Stellar Remnants.

- Missing Physics: (talk by White)

  Enabling the Incorporation of Radio Astrophysics in Multi-Wavelength Astronomy.

***** Presentations from review available online***

VLASS Milestones to Date

Date	Activity
2013 September	Call for White Papers
2014 January	VLASS Planning Workshop at AAS
2014 February	SSG convened
2014 March – June	SSG finalizes science definition
2014 October 15	Proposal submitted for internal review
2014 Oct. 15 – Dec. 1	NRAO Internal Review
2015 January 15	Final proposal posted for community comment
2015 February 15	Community commenting closed (for Community Review)
2015 March 4 – 6	External Community Review (Socorro)

https://science.nrao.edu/science/surveys/vlass/timeline-structure

VLA SKY SURVEY

VLASS: Survey Definition

- Comprehensive multi-use legacy survey.
  - Enables wide ranging studies (multi-wavelength, statistical, time domain)
- All in S-Band (2 – 4 GHz), B/BnA-configurations
  - Full Polarization – Improved RM Synthesis Imaging over L-band
  - Less stringent dynamic range requirements than L-band
  - High Angular Resolution Imaging (2.5”)
  - Synoptic – 3 epochs, 120mJy/beam per epoch, 32 month cadence
- SKA 1.4 GHz Pathfinder Surveys Considered
  - Complements: ASKAP/EMU, APERTIF/WODAN, MeerKAT/MIGHTEE
  - Sensitive to same population of sources
  - ***Frequency better suited for explosive event timescales***
  - ***Unique depolarization space***
- ~5400hr investment over ~7yr (~15% impact on PI time)

	Area (deg^2)	Resolution (”)	Rms (μJy/bm)	Time (hr)	Epochs
All-Sky	33,885 (δ > -40°)	2.5	69	5436	3

All-Sky comparisons (past)

Parameter	VLASS – ALL SKY	VLA – NVSS	VLA – FIRST
Frequency (MHz)	2000 – 4000	1365, 1435	1365, 1435
Bandwidth (MHz)	2000	84 (2x42)	42 (2x21)
Area (sr)	3.3π	3.3π	π
rms (μJy bm^{-1} / K) ✚	69 / 1.5	260 / 0.018	88 / 0.41
Resolution (")	2.5	45	5.4
Source Density (deg^{-2})	~280	~60	~100
Total Sources (10^6)	~10	~2	~1
Start Date	May 2016	complete	complete

✚ rms values scaled to 3GHz assuming $S_\nu \sim \nu^\alpha$ where $\alpha = -0.7$

VLA SKY SURVEY

All-Sky comparisons (future)

Parameter	VLASS – ALL SKY	ASKAP/EMU	Apertif/WODAN	LOFAR "Tier 1"
Frequency (MHz)	2000 – 4000	1130 – 1430	1130 – 1430	120 – 180
Bandwidth (MHz)	2000	300	300	50
Area (sr)	3.3π	3π	π	2π
rms (μJy bm^{-1} / K)✚	69 / 1.5	12 / 0.016*	12 / 0.008	12 / 0.039
Resolution (")	2.5	10	14	6.5
Source Density (deg^{-2})	~280	~1460	~1480	~1360
Total Sources (10^6)	~10	~45	~15	~28
Start Date	May 2016	2016?	July 2016	ongoing

✚ rms values scaled to 3GHz assuming $S_\nu \sim \nu^\alpha$ where $\alpha = -0.7$

* Given current PAF performance and number of antennas expected, we assume 20 μJy bm^{-1} is more realistic than the goal 10 μJy bm^{-1}

Qualitative Improvements with VLASS

(combination of: ν, Δν, θ_s)

Key Science Goals Require *Resolution*

- Transients – Cadence and Frequency better suited for identifying cosmic explosions + Resolution to localize events (nuclei vs. disk events) + Bandwidth for characterization

- Polarization – Unique depolarization space + high Resolution allowing for RM ***mapping*** (ground-breaking).

- Exotic Pulsars – Resolution + Bandwidth allow for efficient identification.

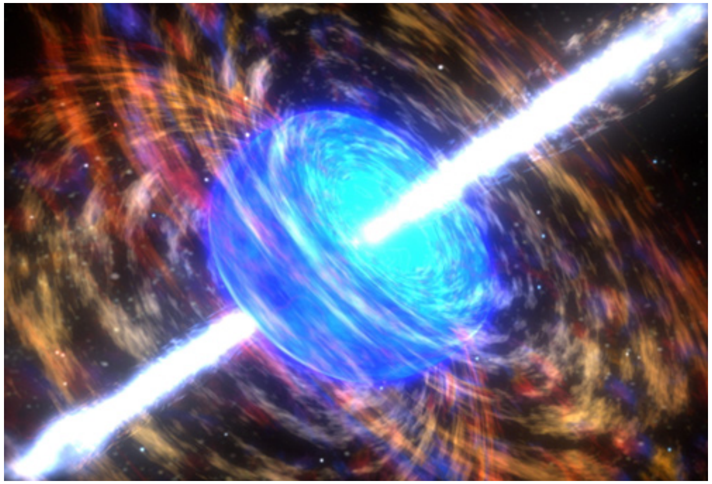
Un-obscured view of cosmic explosions

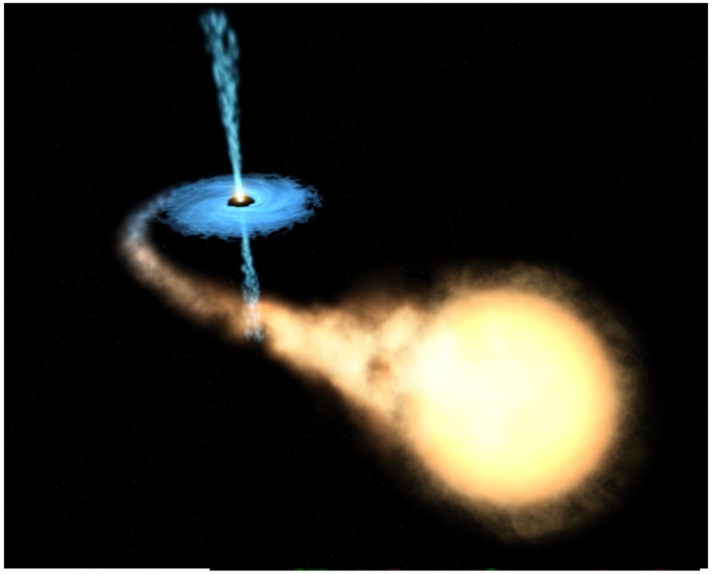
- ***VLASS will be the first synoptic radio survey to detect large samples of explosive transients***

Examples:

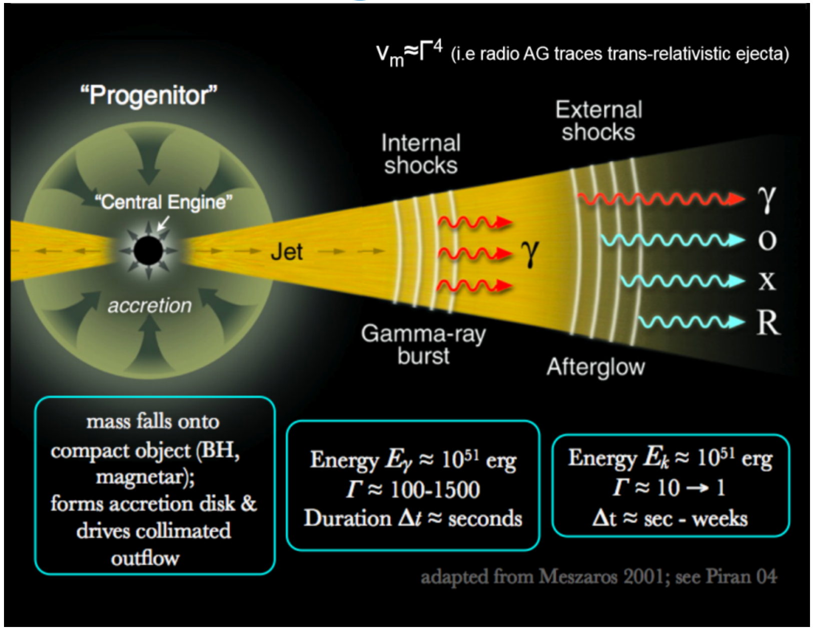
- AGN and Microquasar jets
- Supernovae & GRBs afterglows
- Black hole tidal disruption events (TDEs)
- Giant flares from magnetars

- *Localize events in galaxies (disk vs. nuc.)*
- *Maximize detection rate at S-band*
- *Measure true rate and energetics without having to assume beaming fractions*
    - Obscured supernovae in dusty environments
    - GRB orphan afterglows
    - Binary neutron star mergers





BNS-mergers in the Gravitational Wave Era



- Advanced LIGO (aLIGO) and Advanced Virgo (AdV) coming online
- Binary neutron star (BNS) coalescence the most likely source detected
- Associated γ-ray burst is highly beamed - true rate poorly constrained
- Radio afterglows are isotropic – detectable with the VLA (Nakar & Piran 2011)
- ***VLASS will provide an unbiased measure of the BNS-merger rate***

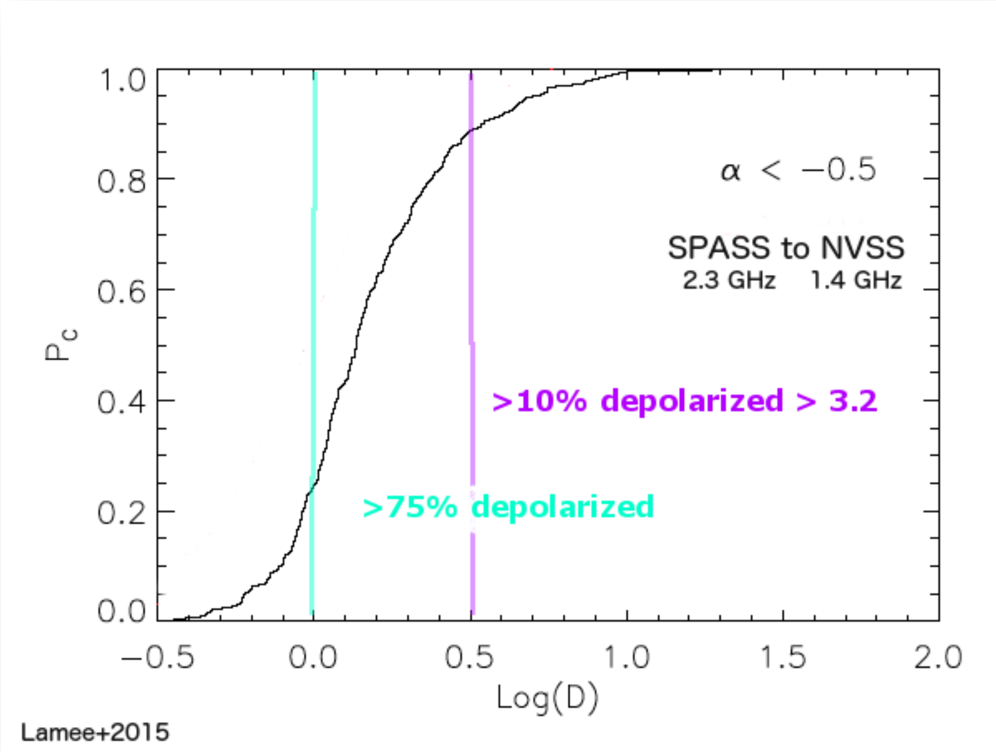
Probe depolarized population

Only ~3% sources polarized – why ?

Bandwidth Depolarization

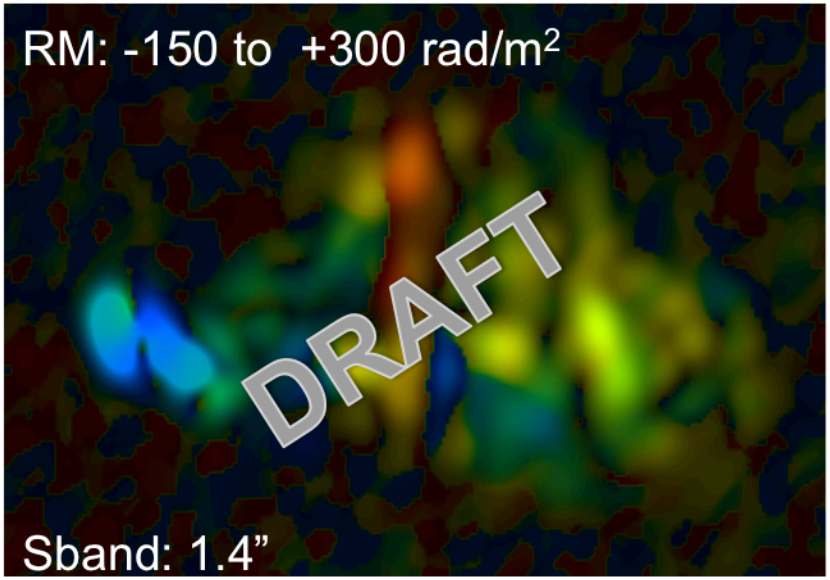
NVSS (full bandwidth)	|RM| max < 100 rad/m²
NVSS (split bandwidth)	< 500 rad/m²
VLASS	< 13000 rad/m²

Physical Depolarization



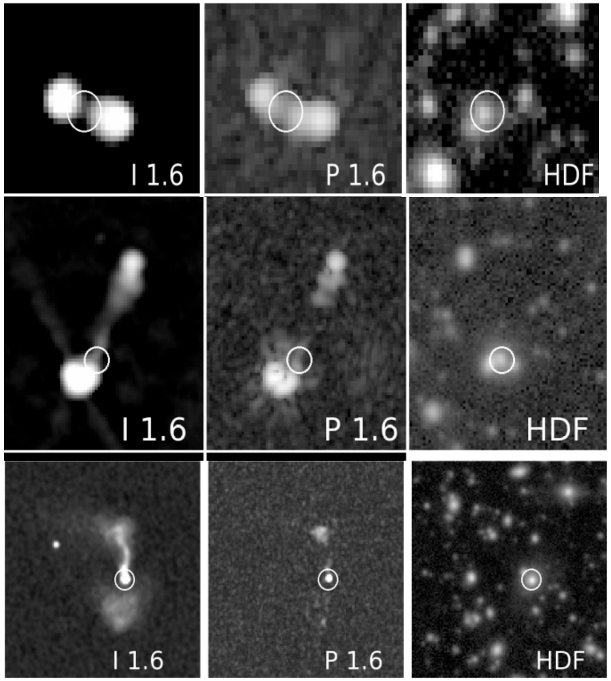
- ***First ~arc-second all-sky polarization survey***
- High freq.+ res. → depolarization effects dramatically reduced
- S-band optimal for physical depolarization (Faraday dispersion) of 50-100 rad/m² (Arshakian & Beck 2011)

Produce Faraday maps

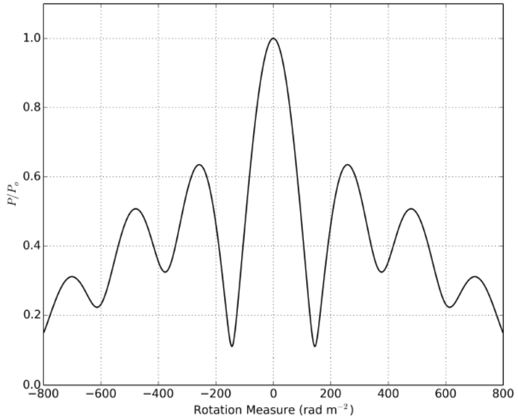


(A2256 Source A, Rudnick, Owen Eilek, 2015)

With NVSS 45”, all unresolved.



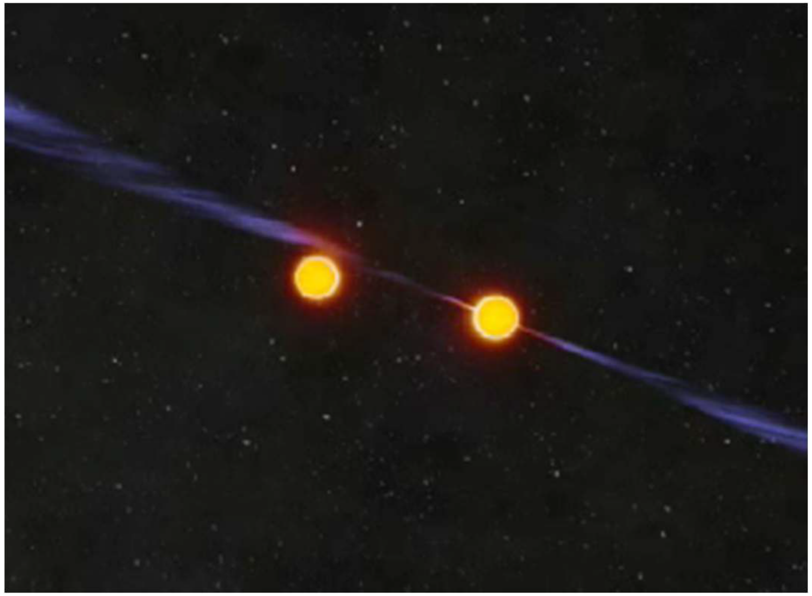
GOODS N, 1.4 GHz, 1.6” resolution
10 of 14 polarized sources resolved
Median size ~20”
Rudnick & Owen 2014



Faraday Transfer Function
RFI-free 2-4 GHz
Resolution=
200/[2*S/N] rad/m^2
3.8” resolution

Efficient Identification of Exotic Radio Pulsars

- Identify candidate radio pulsars as compact, steep spectrum sources.
  - Multi-wavelength source matching to eliminate majority of sources.
  - Follow up selected candidates with deep time domain observations.



- Complements traditional time-domain search (periodicity and pulse dispersion).
  - Robust against time-domain RFI.
  - Very different selection effects.

Highlights:

- Ultra-compact binaries (NS-NS, NS-BH): test theories of gravity.
- Ultra-fast pulsars (sub-ms): equation of state for ultra-dense matter.
- Intermittent objects: transient emission.

= Significant biases against these objects in traditional time-domain surveys.

VLASS Basic Data Products

(To be hosted by NRAO)

Type	Description	Size	Notes
Visibilities	Immediate	489 TB	Raw data and calibration products.
Images	Quick-Look	29 TB	Stokes I and uncertainty.
	Single-epoch	101 TB	7 images covering Stokes I,Q,U, α_{I}, and uncertainties.
	Cumulative	48 TB	As above + curv$_{\mathrm{I}}$, tapered images (1/3 nominal resolution).
Image Cubes	Coarse single-epoch	101 TB	Source cutouts: 5 images (I,Q,U and uncertainties) for 14 $\times$ 128 MHz bands. Only 10% of sky ($\sim 10^6$ sources).
	Coarse cumulative	37 TB	As for single-epoch coarse cubes, plus a tapered set of images.
	Fine cumulative	119 TB	As for cumulative coarse cubes, but for 179 $\times$ 10 MHz channels and cut outs for 2.5% of whole sky.
Catalogs	Single-epoch	Small	Location, shape, brightness, spectral index, and polarization.
	Cumulative	Small	As for single-epoch case.

VLA SKY SURVEY

Enhanced Data Products/Services Requires a community led effort!

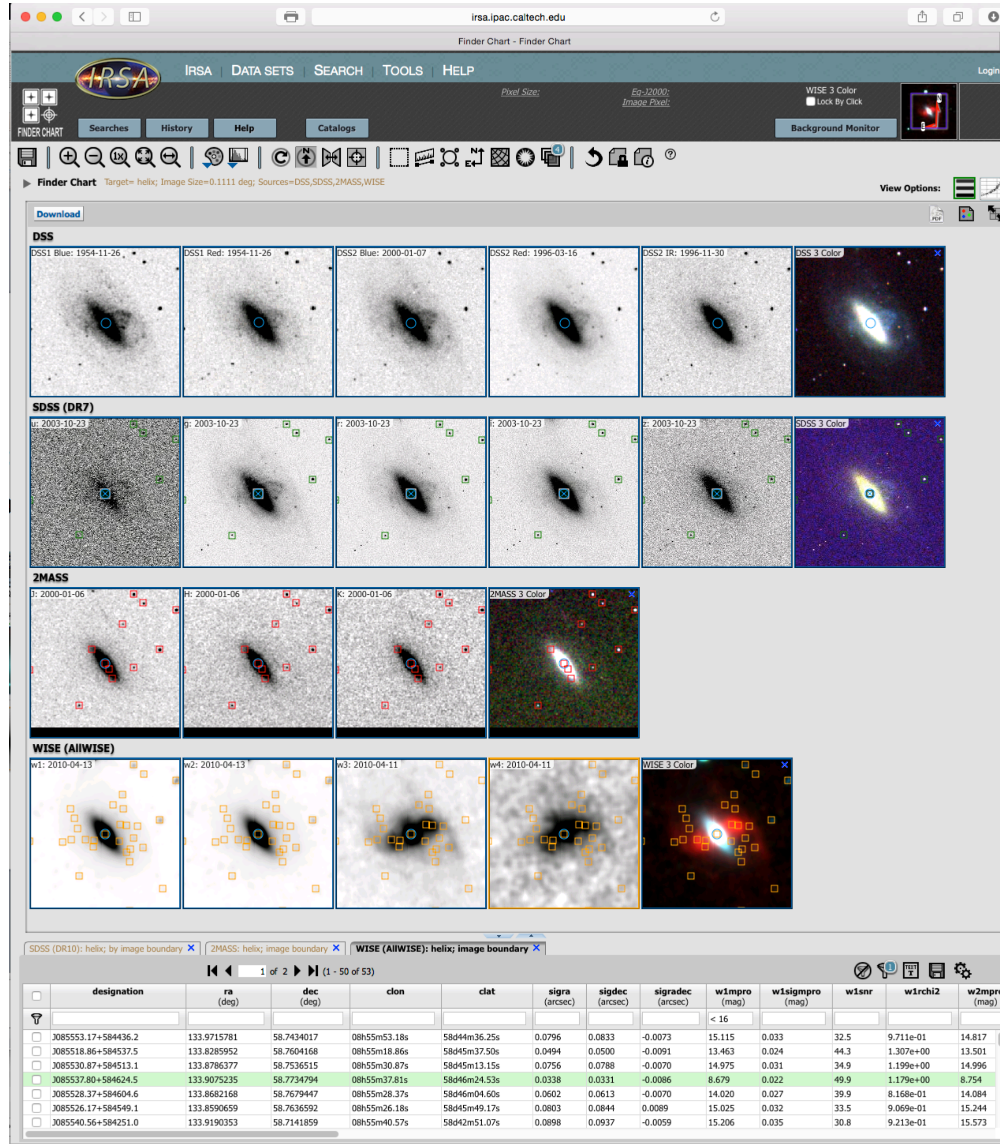
Activity	Description	Notes
Catalogs (MA: A)	Identify objects	Gathering raw output of source detection into associations ("sources") with classifications.
	Polarimetry	Cataloging polarimetric information (RM, $\sigma_{\rm RM}$) for multiple components and assembled sources.
	Transients	Robust, rapid transient identification in quick-look data.
Transients (MA: B&C)	Alerts	Rapid announcement of transients, initial classification.
	Fast transients	Time cut-outs of visibility data for sub-second transients.
Polarimetry (MA: D)	Faraday cubes	Cut-out cubes of complex spectrum with δRM $= 10$ rad m^{-2}.
Archiving (MA: E)	Data hosting	Single-epoch images, cumulative images, spectral cubes.
	Data services	Querying, band-merging, associating.
	Citizen Science	Radio Galaxy Zoo and more.

VLASS Legacy Archive

- To be hosted by ***IPAC/IRSA***

  VLASS data will to be integrated with, e.g., *Spitzer*/, *Planck*, WISE. Euclid, PTF+ZTF, etc…

- Enhanced data products lead to heavy community usage: ***>50% of all Spitzer publications make use of Legacy Program Products***



VLASS Future Milestones

Notional schedule (as of October 2015)

Date	Activity
2015 March 4–6	External Community Review (Socorro)
2015 March – 2015 Oct	Set up Project Office, draft workplan, allocate resources
2015 March – 2016 May	Test & Development Program carried out
2016 January	VLASS Preliminary Design Review (PDR)
2016 May 27	Start of 2016A B-config (VLASS pilot observations possible)
2016 June	VLASS Critical Design Review (CDR), final go/no-go
2016 Aug 29	End of 2016A B-config (nominal, without VLASS)
2016 Oct 3	End of 2016A B-config (with a 1 month extension for VLASS)
2017 Apr 3	Delivery of B-config Epoch 1 (6 months: ALL-SKY Stokes I only)
2017 Oct 3	Delivery of B-config Epoch 1 (12 months: Pol.)
2017 Sep	VLASS Cycle 2 observations commence (B-config)

VLASS: Take away message

- A new era of both deep field and wide-area multi-wavelength synoptic surveys is about to begin!
  - ***Enter VLASS: A multi-use public legacy survey***

- VLASS will support a broad community & enable wide range of science and discovery
  - Concentrating on capabilities that are complimentary (e.g., not achievable) by SKA pathfinder surveys
  - ***Hidden explosions, Faraday Tomography, Galaxies & AGN Everywhere***

- VLASS builds on the past, and looks towards the future
  - Snapshots of our Universe unique in time & space!
  - A springboard into the LSST and SKA science era
  - A substantial real world test-bed for SKA science and processing