LWA-1 Science Overview

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Key LWA Science Drivers

- Acceleration of Relativistic Particles in:
  - Hundreds of SNRs in normal galaxies at energies up to 10^{15} eV.
  - Thousands of radio galaxies & clusters at energies up to 10^{19} eV
  - Ultra high energy cosmic rays at energies up to 10^{21} eV and beyond. — Besson
- Cosmic Evolution & The High Redshift Universe
  - Evolution of Dark Matter & Energy by differentiating relaxed & merging clusters
  - Study of the 1st black holes & the search for HI during the EOR & beyond — Greenhill, Hartman
- Plasma Astrophysics & Space Science
  - Ionospheric waves & turbulence — Helmboldt, Rickard
  - Acceleration, turbulence, & propagation in the ISM of Milky Way & normal galaxies.
  - Solar, Planetary, & Space Weather Science — White, Jaeger
- Transient Universe
  - Possible new classes of sources (coherent transients like GCRT J1745-3009) & Pulsars
  - Magnetar Giant Flares
  - Extra-solar planets
  - Prompt emission from GRBs

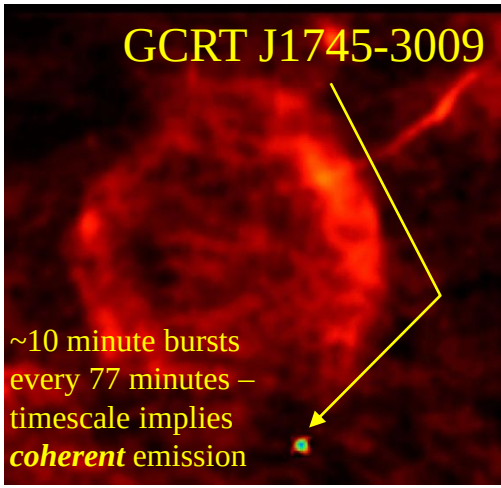
Ellingson, Hartman, Hallinan, Hankins

Top level LWA science drivers well represented at this meeting & in early science commissioning activities

LWA-1 Science: Transients

- Earlier HF/VHF (dipole) efforts – GASE, ETA, LWDA, LOFAR, MWA, etc
  - Many emphasize all-sky observing and real-time de-dispersion capability
  - Focused on search for prompt, coherent radio emission from GRBs

Hyman et al. 2005

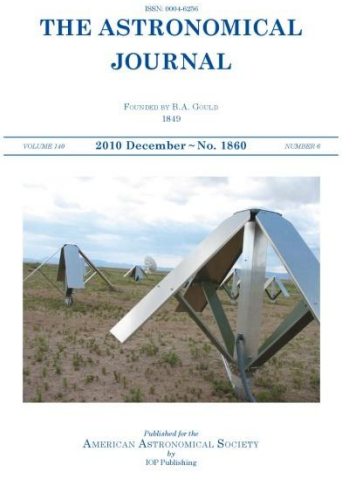


- An advantage/complement of LWA-1 beam-forming is angular resolution & sensitivity – suggested programs include
  - Target known candidates at multiple frequencies
    - Multiple beams at different ν to provide wide bandwidth
    - Targets inc. GRBs, Crab Pulsar, Galactic Center, nearby flare stars, known exo-planetary systems
  - Serendipity-driven – target numerous fields
    - Survey entire sky by pointing multiple-ν beams at a different field each day, or
    - Form fan-beam by stacking multiple single-ν beams along meridian
      - Latter emphasizes sky coverage over bandwidth
- New opportunities include simultaneous observations with EVLA Low Band

Advantage over earlier VLA & GMRT: inflate Ω*t through long dwell times

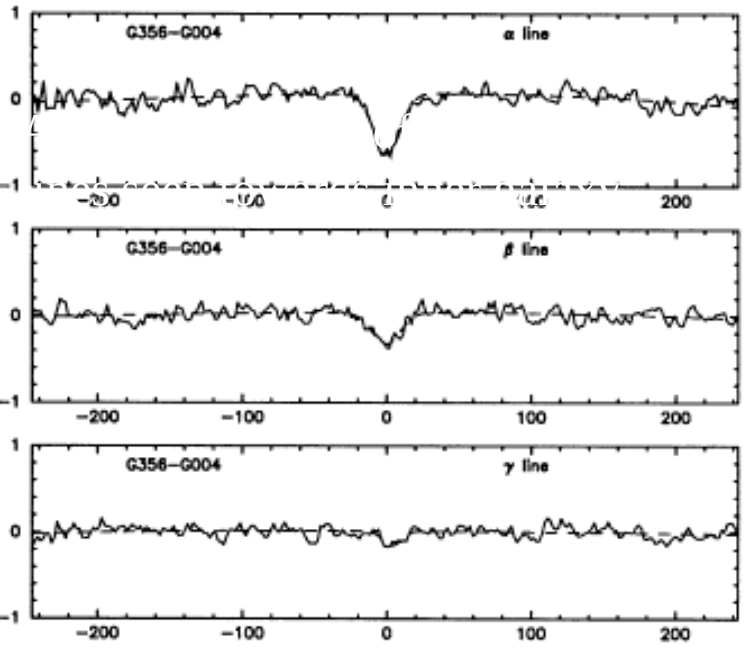
Transient Science Commissioning

- Proposal LE001: A GCN-triggered Search for GRB Prompt Emission (**Ellingson**)
  - Science: Theoretic predictions include bright (> 100 Jy), coherent emission processes
  - Comm: MCS triggering, RFI mitigation, pulse detection & incoherent de-dispersion software
- Proposal LE002: Crab Giant Pulses (CGPs - **Ellingson**)
  - Science: Low frequency monitoring, underlying mechanism
  - Comm: RFI mitigation, pulse characteristics, on-line CGPs detection techniques/analysis software
- Proposal LS001: Single Dispersed Pulses (Simonetti, **Ellingson**)
  - Science: Exotica, including explosions of primordial black holes (PBHs)
  - Commissioning: RFI mitigation, pulse characteristics
- Proposal LT001: Observing the Transient Universe with the 1st LWA Station (Taylor, **Hartman**)
  - Science: All-sky transient monitoring
  - Comm: Building all-sky imager backend, software correlation, RFI excision
- Proposal LH-002: Searching for Hot Jupiters with the LWA1 (**Hallinan**)
  - Science: Detection of magnetized, extrasolar planets
  - Commissioning: Search algorithms for bursty & circularly pol. emission
- Proposal LB001: LWA Cosmic Ray Air Shower Trigger (**Besson**)
  - Science: Source of UHE Cosmic Rays – AGNs?
  - Commissioning: External triggering capabilities (on analog signals), providing analog coincidence unit



Lazio, Clarke et al. 2010

LWA-1 Science: ISM Studies using RRLs



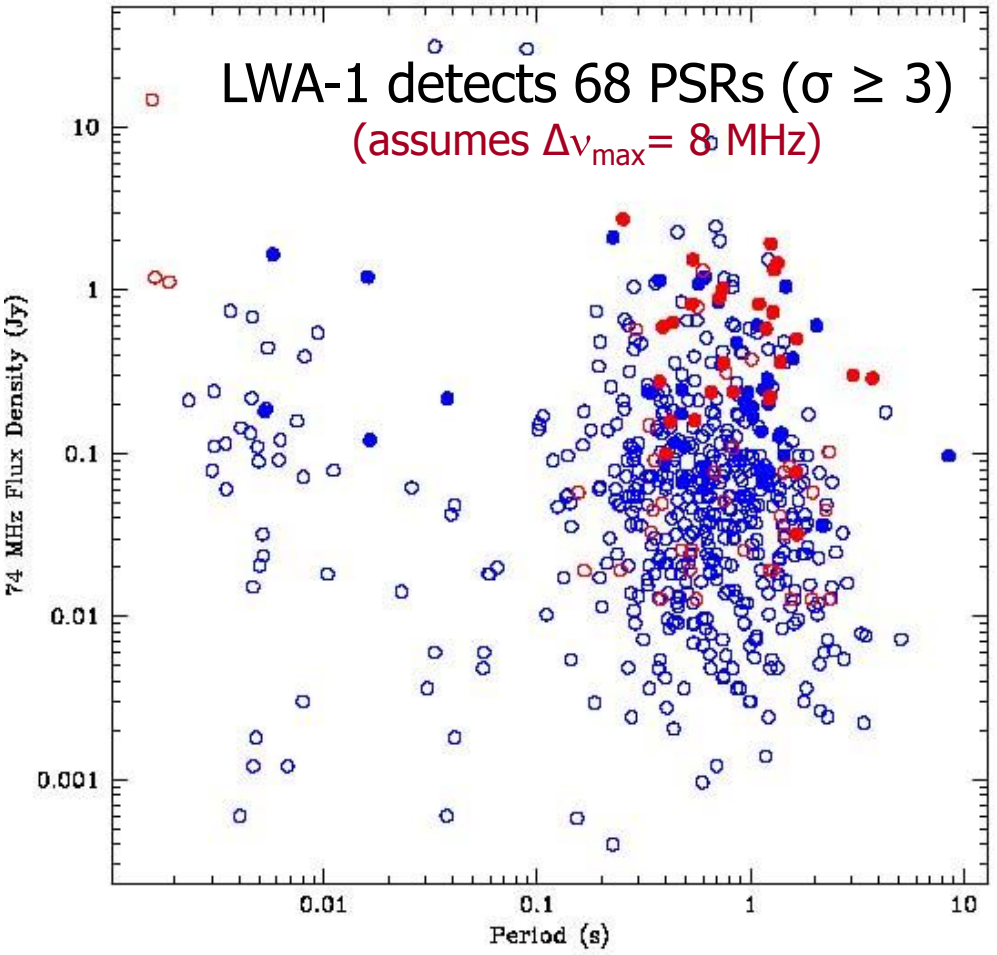
Erickson et al. 1985

- Sensitivity Calculation
  - 1 line, 1 polarization: 10 hours
    - Frequency independent
    - $\propto$ [filling factor]$^{-2}$
- Single LWA Station
  - Can do several lines at once, 2 pol
  - Detect in ~ [5,25] hrs @ [≤40,74] MHz
  - Higher frequency work takes more time
    - Need access to lowest LWA ν range
  - Need $\Delta\nu$=0.1 KHz (1-2 km/s @25 MHz)

LWA-1 will push beyond Parkes - a Galactic plane survey (student thesis?) is very feasible.

LWA-1 Science: Feasibility of Detecting Pulsars

- Target bright, low DM pulsars
- Source list developed from
  - Flux density based on measured or extrapolated spectrum
  - NE2001 scattering model used to estimate pulse broadening
    - Combined with known PSR periods to pick sources that will not be scatter broadened away
  - Simulated LWA-1 Pulsar Observations – Jacoby et al. 2007 (LWA Memo 104)



Over 60 PSRs detectable with LWA-1!

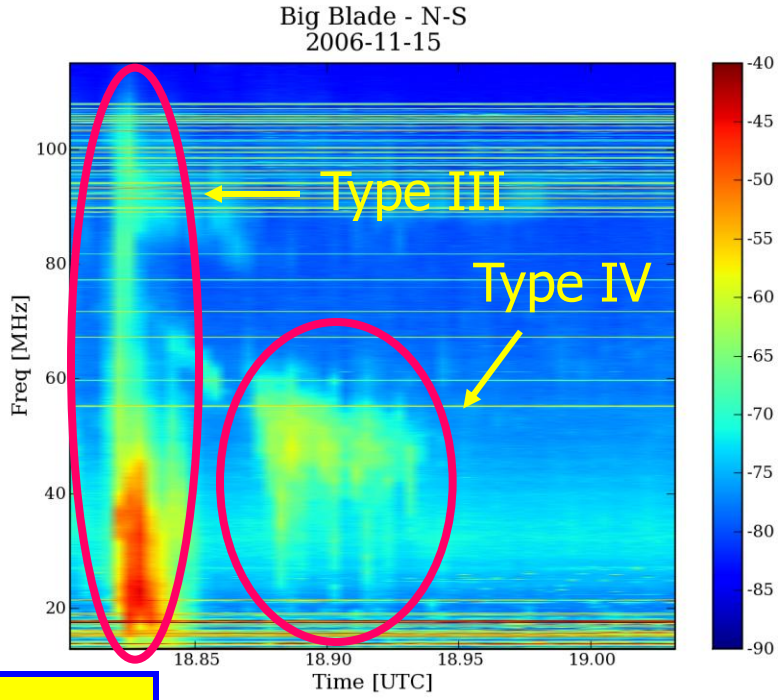
RRL, Pulsar, & other Galactic Science Commissioning

- Proposal LP001: Carbon Recom Lines in the Cygnus Arm (Pihlstrom, **Lane**)
  - Science: Physical processes in the cold, low density ISM (Peters et al. 2010 A&A, Dark Ages contaminant
  - Commissioning: Spectral line capability test, RFI mitigation
- Proposal LR001: Low Frequency Studies of Pulsars (Ray, **Hankins**)
  - Science: Pulsar emission mechanism, geometry of emitting region
  - Commissioning: Array phasing capability, integrated spectra, pulse profiles
- Proposal LH001: Continuing Measurements of the Cas A/Cyg A flux ratio (Hartman)
  - Science: Cas A temporal variations – follow-on to LWDA science (Helmboldt & Kassim 2009)
  - Commissioning: Amplitude calibration, beam pointing, zenith beam pointing check, off-zenith pointing, transient response test, beam shape measurements, sensitivity as a function of frequency
- Proposal LP002: Multi-frequency Large Scale Sky Survey (**Polisensky**)
  - Science: Galactic & extragalactic emission processes, subtraction of foreground emission for high-z HI work, HII absorption
  - Commissioning: Sky maps, spectral index maps

LWA-1 Science: Solar System Studies

- Solar
  - Some solar bursts may have fast (~50 ms), narrow-band (<10 kHz) structure requiring more sensitivity than existing single-dipole monitoring systems (e.g. Big Blade, GBSS or BIRS)
    - See papers by G. Mann & G.P. Chernov
  - LWA-1 will allow 16X higher temporal or spectral resolution at comparable S/N to ongoing single dipole monitoring programs
- Jupiter
  - Voyager saw wealth of fine temporal & spectral structure in decametric bursts that require sensitivity of LWA-1 to observe from Earth
    - ms time resolution will be useful

Solar bursts currently being studied with single antenna systems, including LWA dipoles



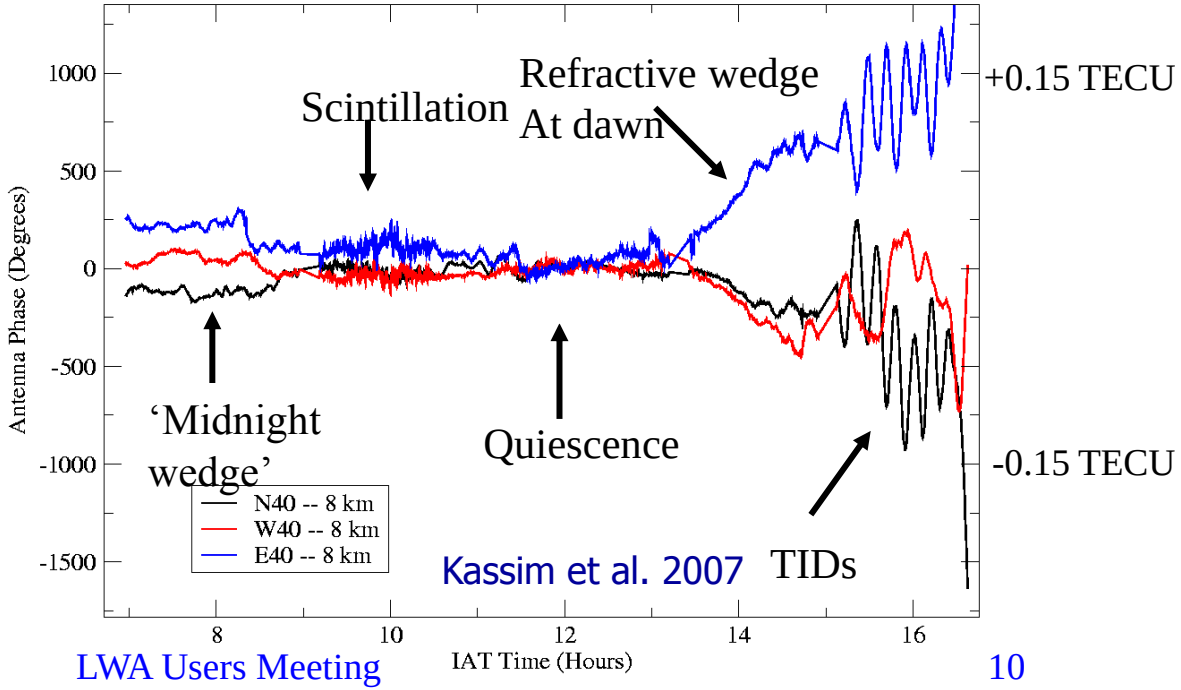
Both applications need broad frequency range

Solar System Science Commissioning

- Proposal LC001: Tracking the Dynamic Spectrum of Jupiter (Clark**e**, **Jaeger**)
  - Science: High temporal & spectral resolution studies of decametric emission, emission storms, S-burst structure, polarization conversion
  - Commissioning: Polarization, temporal & spatial variations
- Proposal LW001: Solar Radio Bursts at High Temporal and Spectral Resolution (**White**)
  - Science: Solar radio bursts characteristics
  - Commissioning: Dynamic spectra, polarization

Ionospheric Measurements: Interferometry (e.g. with LWA 2)

- A LW interferometer is extremely sensitive to ΔTEC
  - Current VLA has ΔTEC precision ≤ 10^{-3} TECU [1 TECU ≡ $\int n_e dl \sim 10^{17}$ m^{-2}]
- LWA's power is ability to measure ΔTEC towards <u>many</u> simultaneous directions
- Basic building blocks of those measurements are the phase measured between any two stations
- As soon as LWA-2 is available, we can start exploring those kinds of measurements
- How well do ionospheric phases & phenomena vary with frequency?
- Build up ionospheric weather almanac
- Helmboldt talk tomorrow

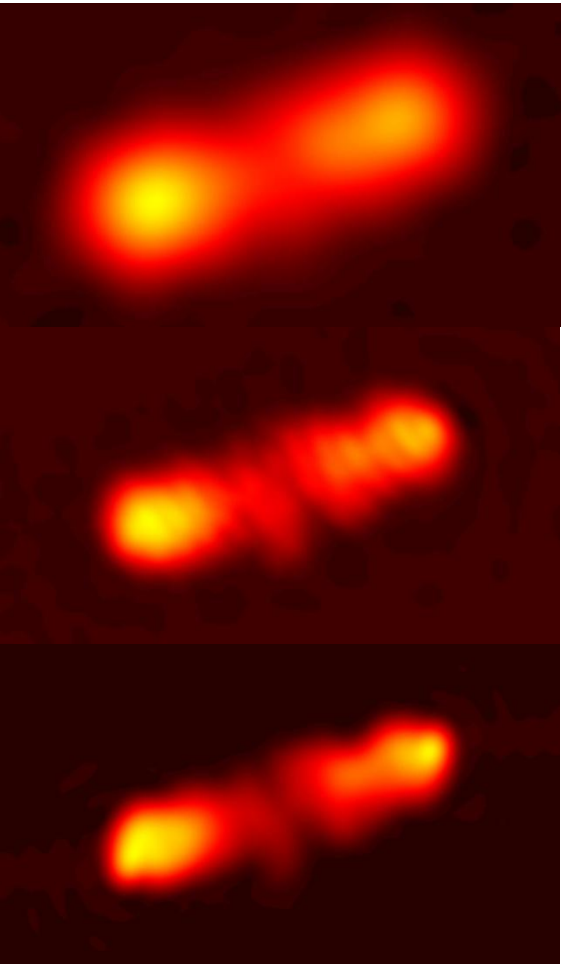


Ionospheric Science Commissioning (standalone with LWA-1)

- Proposal LR002: Ionospheric Absorption Measurements Using LWA-1 as an Imaging Riometer (**Rickard**)
  - Science: Ionospheric total electron content
  - Commissioning: Evaluate the use of LWA1 to extract riometry data
- Proposal LC002: Ionospheric Scintillation (Crane)
  - Science: Extract 2-D ionospheric spatial structure
  - Commissioning: Ionospheric behavior, aim to establish protocol for studying the ionosphere
- Proposal LC003: Passive Meteor Scatter using the Long Wavelength Array (Close)
  - Science: Meteor trail passive illumination from TV at VHF - develop improved understanding of radar scattering mechanisms
  - Commissioning: Pulse event detection algorithms, estimate of ionospheric electron concentration perturbations due to meteor showers for improved LWA calibration

Science with LWA-1+: LWA 2 & 3 with the VLA

LWA-1 has 10X sensitivity of 1 VLA dish – LWA outlier stations can compliment VLA 74 MHz for improved angular resolution on bright objects



- VLA A configuration
  - Limited resolution (Kassim et al. 1993)
- VLA A+ PT
  - Resolution better, fidelity poor because of "lonely" outlier (Lazio et al. 2006)
- EVLA A + PT + LWA-2
  - Image fidelity improved with single outlier at Horse Springs

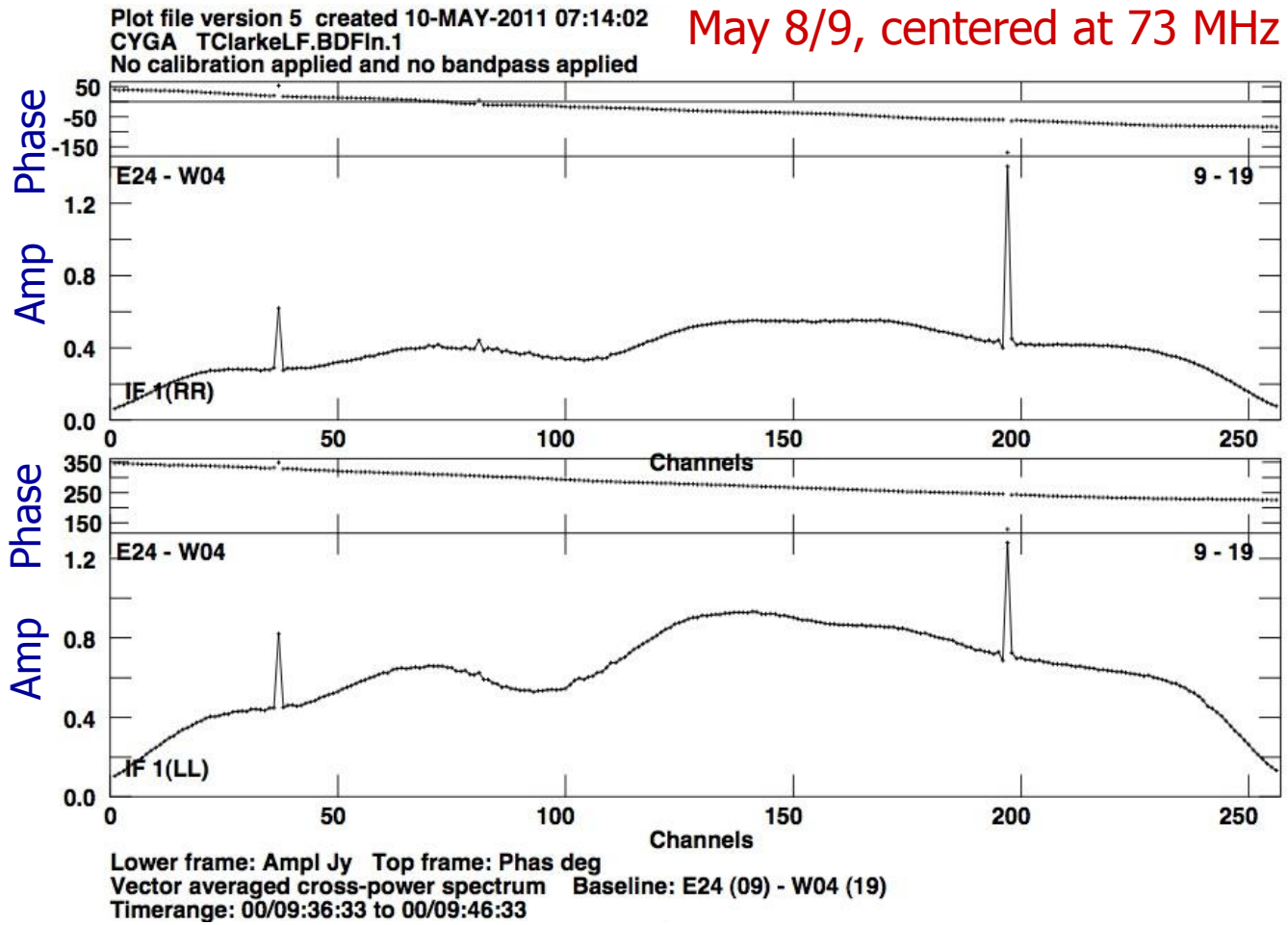
Significant impact even from only 1-2 outlier stations

Summary

- LWA-1 will do good science – ranging from:
  - Potentially very exciting - transients
  - More modest – pulsar, ISM, & solar system studies we know we can do
    - Both extremes represent good science, serendipitous discoveries possible
    - Viable student thesis projects - RRL, pulsar surveys
  - Invaluable commissioning experience - including deep, efficient, multi-purpose integrations as path-finders towards future LWA experiments
- With LWA 2 & 3 – aka LWA-1+
  - Standalone with LWA-1
    - Anti-coincidence RFI avoidance for concurrent transient observations
    - Demonstrate station-based interferometry
    - Determine source locations & flux densities
    - Explore ionospheric scaling laws & phenomenology - test future calibration schemes
  - With EVLA Low Band
    - Monitor EVLA transient observations for lower frequency counterparts.
    - LWA-2 & 3 outliers for EVLA 74 MHz imaging - next step beyond PT-link
    - Improved EVLA 74 MHz system a catalyst to early LWA science
- Useful because LWA stations are BIG.
  - 512 dipoles/station = 75% of Clark Lake array - each 100-m station like GBT
  - Large $\Delta\nu_{max}$ & broad tuning range key to most early (non-imaging) science

Consider placement of LWA-2 to compliment EVLA Low Band: Instant high profile "LWA-EVLA" science

On Sky with EVLA Low Band!



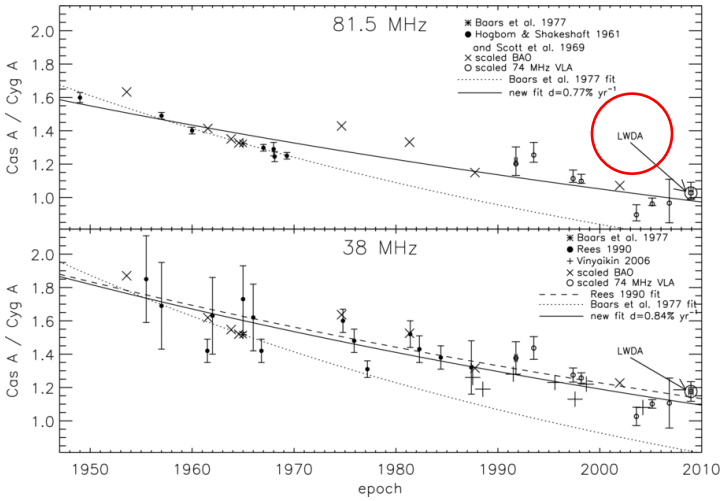
~16 MHz

- Over 10x usable bandwidth over legacy VLA 74 MHz system - can eventually leverage significant portion of LWA bandpass
- Some issues, including RFI, but seems manageable
- Software efforts to handle new data underway (e.g. Bill Cotton, Huib Intema at NRAO-CV & others)

BACKUP

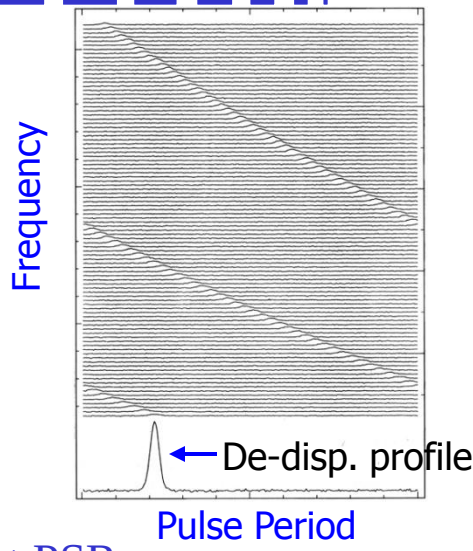
1st Science from LWDA

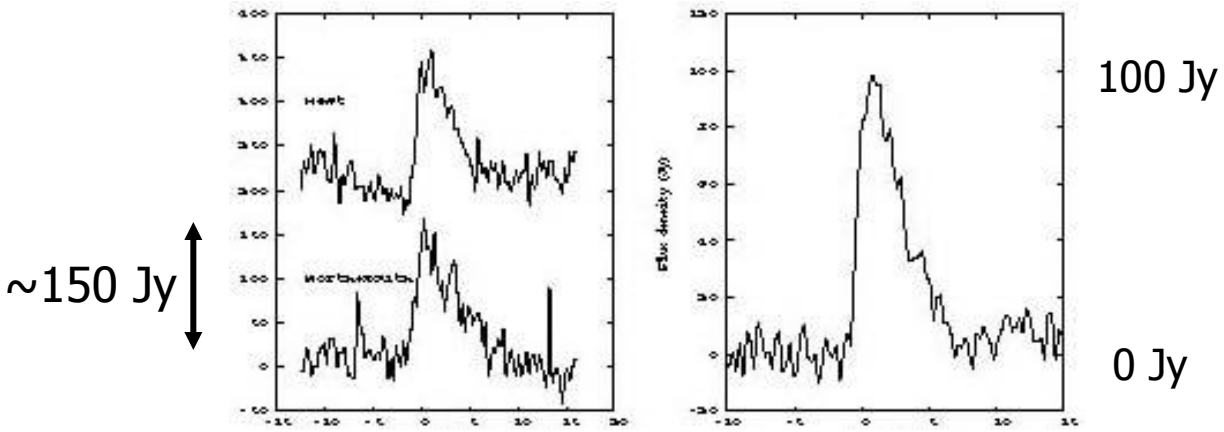
- LWDA is technical legacy of 1st ARI HF/VHF AO
  - 2nd ARI promised scientific results
  - Difficult challenge with NRL forging ahead alone after departure of ARL-UT, minimal UNM support
- 1st scientific paper: Evolution of Cassiopeia A at Low Radio Frequencies **(Helmboldt & Kassim 2009, AJ, 138, 838)**
  - Recipient of ARPAD postdoctoral award
  - NRL press release: http://www.nrl.navy.mil/pao/pressRelease.php?Y=2009&R=79-09r
  - Driven by work of 2 NRL postdocs
    - Helmboldt transitioned to Fed over last year
    - Hartman positioned for NMT role in LWA
- 2nd LWDA science paper ready for submission
- **Realization of LWDA science reflects tenacity & scientific excellence of NRL ARI group**



LWA-1 Science: Pulsars

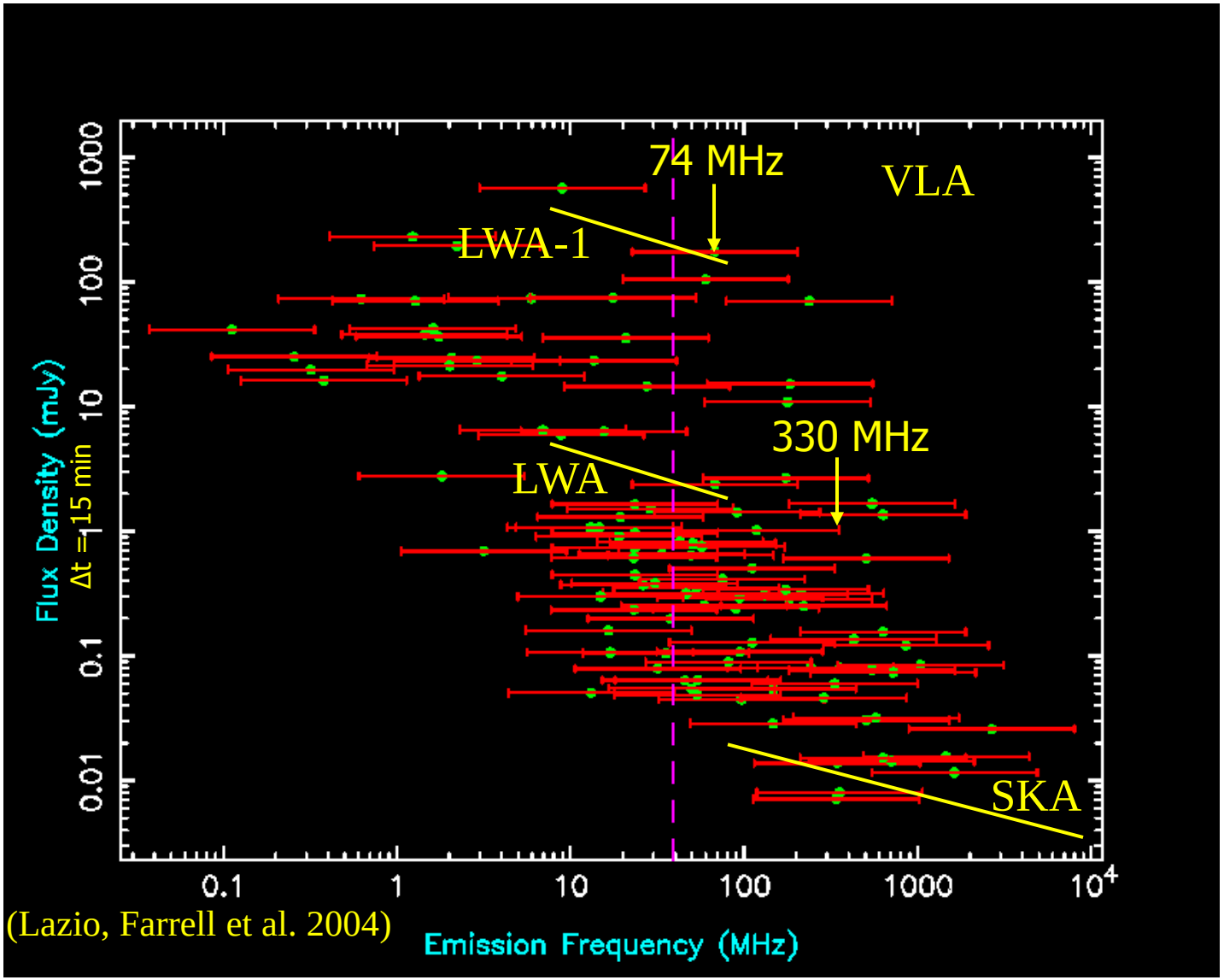
- Detect single pulses via de-dispersion – use to
  - Investigate physics of PSR emission mechanisms
    - Drifting pulses, profiles, inter-pulses
  - Derive pulse-averaged low frequency spectra over LWA range
    - ***Poorly known, especially in lowest LWA frequency range***
- Giant pulses (GPs) & other spurious PSR emission
  - Crab GPs now observed at 23 MHz (Popov et al. 2006)
    - GP spectra do not appear to follow simple power law
  - LWA-1 will search for spurious emission from other nearby, bright PSRs
    - Crab-like GP "echoes" lasting days – possible new probe of small-scale structure within inner synchrotron nebula (Crossley et al. 2006, astroph/0612109)





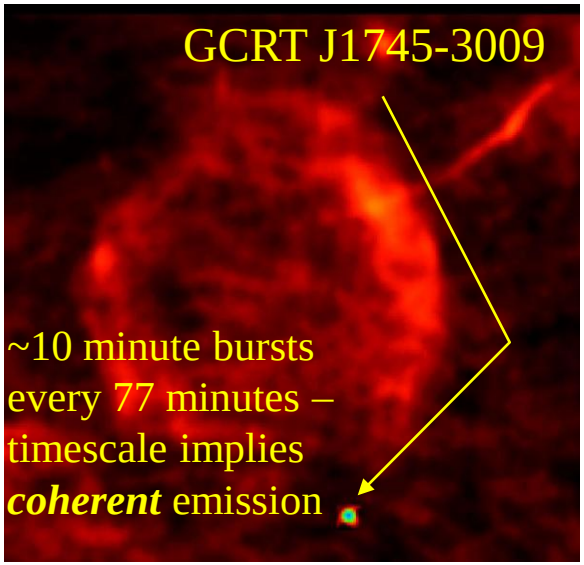
Crab Giant Pulses at 23 MHz: left panel – single pulse in two adjacent frequency channels; right panel – average of 10 strong pulses

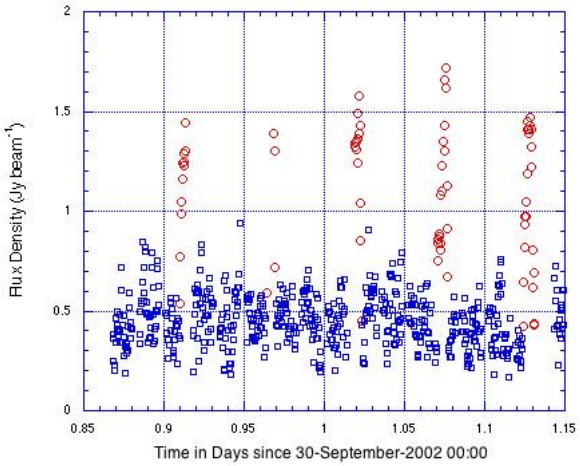
LWA-1 Transient Science: Predicted Planetary Radio Emission



(Lazio, Farrell et al. 2004)

LWA-1 Transient Science: Known Galactic Examples





- Consider GCRT J1745-3009 (Hyman et al. 2005)
  - Bursts: ~ 1 Jy at 330 MHz, ~10 minutes duration
    - If coherent ($S \propto \lambda^6$) – up to 10^4 boost at 74 MHz
  - LWA-1 Detectability
    - 5 min, 8 MHz, 74 MHz: 1σ ~63 mJy
    - Situation 10X worse towards GC
      - T_{sys} ~10^4 K towards GC, A_e down by 2X
      - 1σ ~0.6 Jy; $\geq 5\sigma$ detection if $\alpha \leq -1$
- Consider recent eruption of SGR 1806-20
  - ~ 0.5 Jy at 240 MHz
  - α ~ -2.1 => 5 Jy at 74 MHz – lasts for many days
  - 1 hr, 8 MHz, 74 MHz: 1σ~0.4 Jy➔ >12 σ detection
- These known cases look very feasible
  - Especially considering leverage in Ω*t space

LWA-1 could do exciting transient work!

LWA-1 Science: ISM Studies Using RRLs

Carbon & Hydrogen Radio Recombination Lines are unique diagnostics of the cold ISM at very low frequencies

- Carbon RRLs are of particular interest
  - Detected to very high Rydberg states (up to n~768)
  - Absorption lines below 150 MHz (in emission above that)
  - Atoms very sensitive to interstellar environment - permit excellent measurements of ρ, T, & ionization levels (Payne et al. 1994).
  - Seen all along inner Galactic plane (Erickson et al. 1995)
- LWA-1 offers improvements over other instruments
  - Parkes 64 m: 100 m LWA-1 improves resolution
  - NRAO 300 ft (transit instrument): tracking ability of LWA-1 superior
  - Frequency range: LWA-1 could study the lines at multiple frequencies
    - Essential for understanding underlying physics
    - Wider ν range than Parkes or UTR-2
- RFI will make detection very challenging
  - ***Lines no longer detectable at Parkes***
  - LWA-1 detection: excellent demonstration of ability to do sensitive work in the SW-US

LWA-1 will improve over current capabilities.

Science with LWA-1+

- LWA-1 with LWA-2 & 3
  - Independent operation
    - Anti-coincidence RFI avoidance for transient observations
    - Incoherent addition of RRL observations
  - Interferometry
    - Phase & model fitting to constrain accurate source positions
      - 3 stations increase accuracy via closure phase, ability to measure fluxes
    - Explore deep, interferometric integrations
      - ~65 km baseline: confusion limit ~ few mJy - ***can we get close?***
    - Explore ionospheric scaling laws as tests of future calibration schemes
- LWA-1 with 74 MHz VLA
  - Monitor selected VLA observations simultaneously with LWA-1.
    - E.g., X-ray & radio triggered searches are planned for the GC
    - 74 MHz VLA observations of *SWIFT* triggered GRBs are planned
      - Monitor with LWA-1 at lower frequencies – dispersion an advantage.
- LWA-1+ with 74 MHz VLA
  - Imaging with LWA-2 & 3 outliers as next step beyond PT link
- EVLA exploring possibility to improve 74 MHz capability
  - Improved feeds, increased bandwidth = > ≥10X sensitivity
  - WIDAR correlator might accommodate ≥ 5 LWA stations

LWA-1 Transient Science: Exo-Planet Magnetospheres

- Below 40 MHz, Jupiter, when bursting, is brightest object in solar system
- LWA might detect emission from extra-solar "Jupiters"
  - Independent verification of planetary systems using new technique.
  - Proof of magnetosphere – magnetic shield of cosmic rays pre-requisite for life?
  - LWA-1 pathfinder observations – long shot, but advantage over current VLA searches through longer integrations and at lower frequencies