VLBI "MultiView" Astrometry of Radio Stars

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Stellar Radio Emission

M-dwarfs most ubiquitous stellar type (80%)
Often exhibit activity (flares, CMEs)

- Gyrosynchrotron: mildly relativistic electron population, magnetic field
  - Circular polarization
  - Flare Stars (emission from Chromosphere/Corona), bursty ($<$2 hrs)
  - Güdel-Benz law describes X-ray v.s. radio activity
- ECMI: Electron Cyclotron Maser Instability
  - High circular/elliptical polarization
  - Planetary magnetosphere/aurorae, Jupiter/Io model (star as J), close binaries
  - Can reach GHz with sufficient magnetic field, with high T_B
  - long duration ($>$8 hrs), less variable
  - Possibly periodic due to beaming

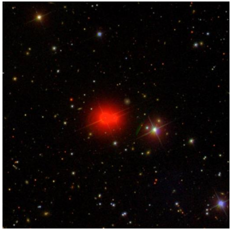


Image Courtesy SDSS DR16

- Astrometry
  - Sub-mas accuracy achievable (relative to phase ref calibrator)
  - Differentiate star vs. companion (e.g. brown dwarf)
  - Resolve binary members (e.g. CR Dra)
  - Extended emission region
  - Reflex Motion
- Polarization
  - EVN achieves 10% polarization accuracy (Stokes-V)
  - Helps discriminate emission mechanisms
- Sensitivity
  - 20 µJy (1σ) in one hour at L-band with the EVN
  - Does require non-thermal emission

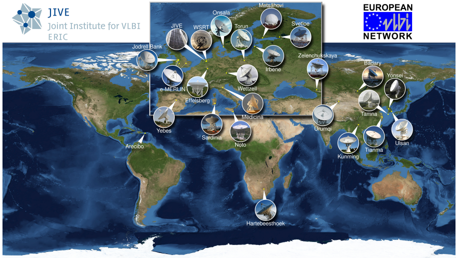
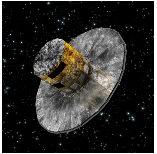


Image by Paul Boven (boven@jive.eu). Satellite image: Blue Marble Next Generation, courtesy of Nasa Visible Earth (visibleearth.nasa.gov).

Accuracy Estimates



Gaia and VLBI reach comparable accuracy

- Gaia EDR3: astrometric uncertainties 0.2-0.5 mas
  - When propagated to VLBI observation epoch
  - For local M-dwarfs (due to brightness); EDR3 improves on DR2
  - Gaia treats sources as single stars (until DR3)
- VLBI resolution: $\sigma_{\text{pos}} \approx \theta_B / SNR$
  - $\theta_B = 1.2 \cdot 18\,\text{cm} / 11,812\,\text{km} = 3.7\,\text{mas}$
  - Simple phase referencing, L-band: 2 mas (limited by ionospheric DDE)
  - Multiple phaseref / Multi-view: order of magnitude better
  - Multiple observations increase accuracy of astrometry
- Astrometric accuracy of phase reference sources: 0.1 - 1 mas
  - Core-shift (e.g. between S-band and L-band)
  - Geodetic (delay based) and astronomical (phase based) position
  - Affects ICRS position; does not affect μ, ϖ

EVN Project EB081: Astrometry of Ross 867 and Ross 868

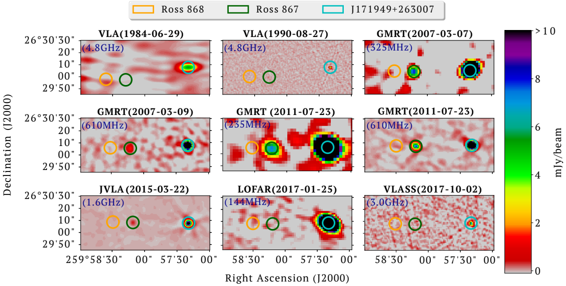
Ross 867 serendipitously (re-)discovered by Huib Intema in archival GMRT data

'Differences in radio emission from similar M dwarfs in the binary system Ross 867-8'
L.H. Quiroga-Nuñez e.a., A&A 633, A130 (2020)

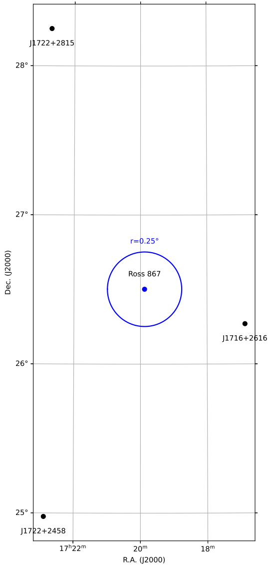
Ross 867: M4.5V (V639 Her, Gliese 669B), optical flaring, variable radio emission
Ross 868: M3.5V (V647 Her, Gliese 669A), optical flaring, no radio detections
Separation: 179.3±0.1 au in projection (no interaction)

- Monitor Ross 867, Detect Ross 868
- Polarization, Variability
- Astrometry with MultiView
- Polarization Calibration (D-terms)
- Understand Emission Mechanism

Three epochs awarded (EB081), +3 (EB091)



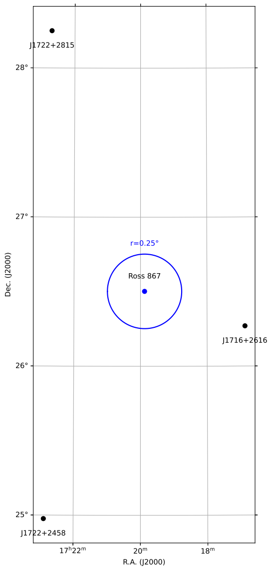
EB081 Phase Referencing

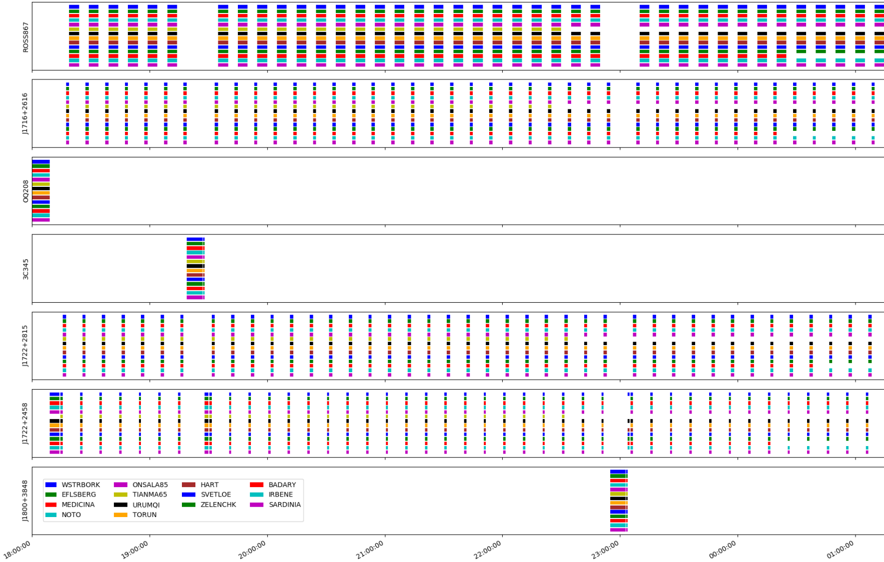


- Selected from AstroGeo (L. Petrov e.a.)
  - Close to science target
  - Sufficient (compact) Flux
  - Low positional error (≤ 0.25 mas)
  - Good MultiView coverage

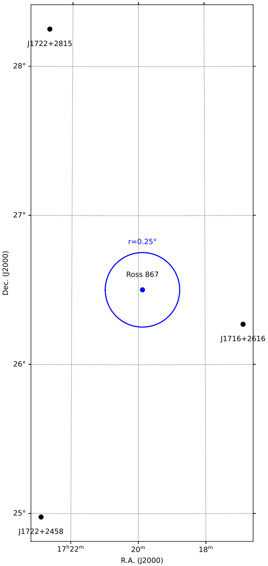
- **J1722+2815** $d = 1.78°$, $S = 165$ mJy, $\sigma_{pos} = 0.16$ mas
- **J1716+2616** $d = 0.76°$, $S = 121$ mJy, $\sigma_{pos} = 0.13$ mas
- **J1722+2458** $d = 1.73°$, $S = 249$ mJy, $\sigma_{pos} = 0.25$ mas

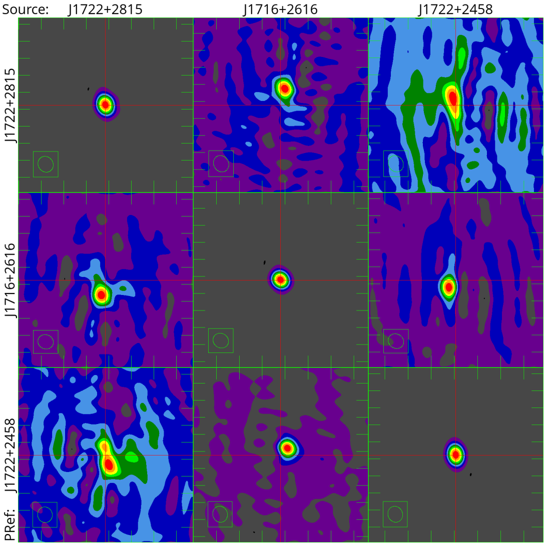
EB081 Phase Referencing





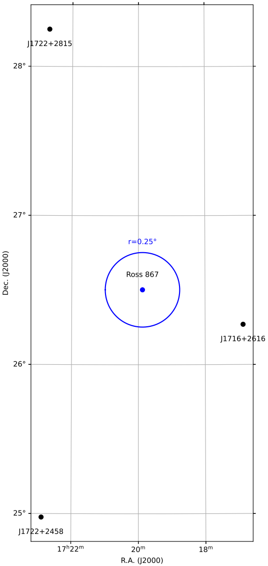
EB081 Phase Referencing

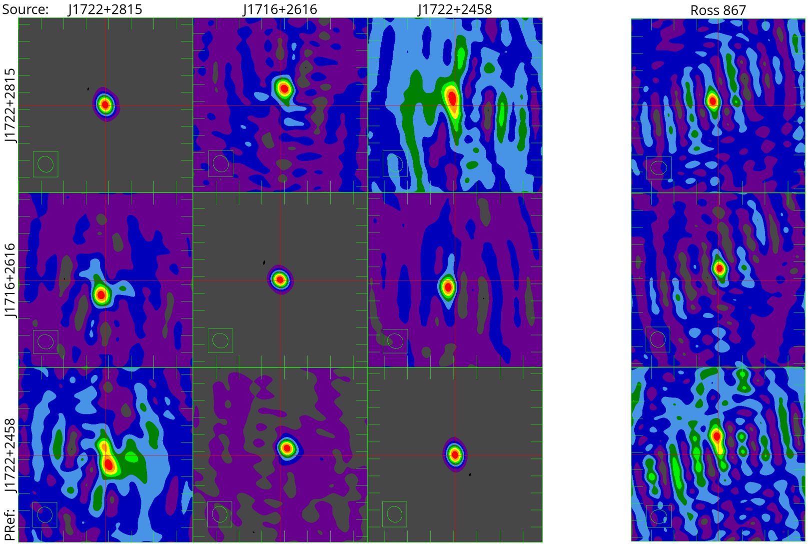




- Gentle A&P selfcal on phase reference targets
- Imaged against each other
- Scale:
  Dec. ticks: 5 mas
  R.A. ticks: 6.7 mas
- Note the symmetries

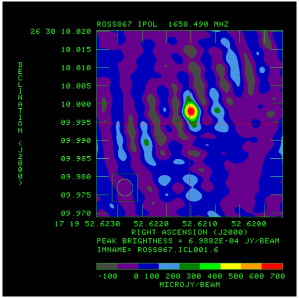
EB081 Phase Referencing

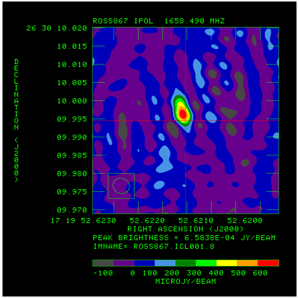




Barycentric Interpolation

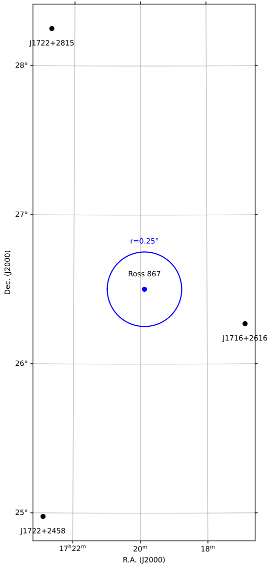
- Measure the interferometer phase at the three phase reference targets
  - Fringe each PR target, from the calibrated primary PR target
  - Phase of the primary PR will be zero
- 2D linear interpolation of phase: slope and direction
- Unwrapping may be needed (and is tricky)
- Keep or remove fixed PR offsets? Plan: average over observing epochs, remove

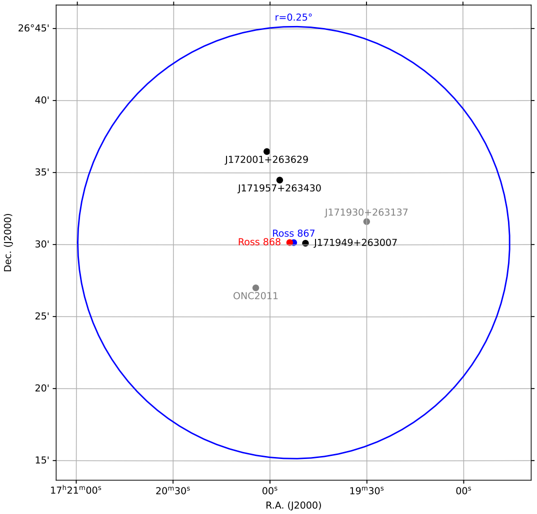




- Left: Phaseref on closest source
- Right: Interpolated (preliminary result)
- Loss of flux, but better S/N

In-beam sources and Primary Beam Correction

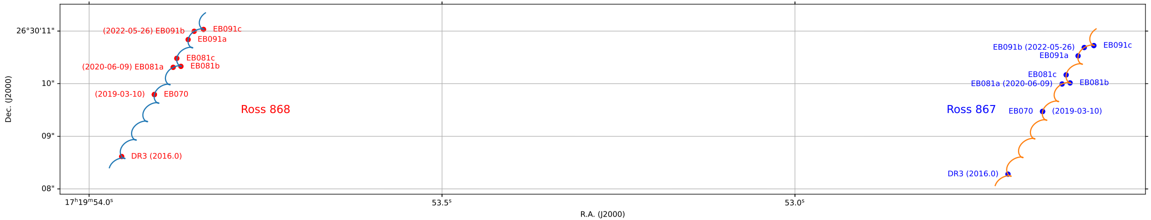




- From VLA archive (Osinga & van Weeren)
- Stationary
- Non-variable
- Test of interpolation
- Requires PBC corrected data
- AIPS: Unique source-id numbers!
- Detected 3 out of 5

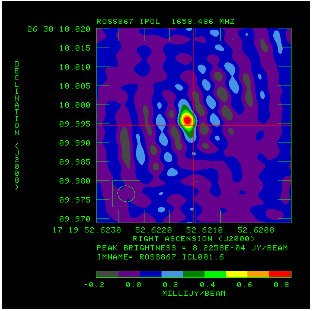
Proper Motion, Parallax, and Coordinate Frames

- Nearby sources: large parallax and proper motion
  - Ross 867: $\varpi = 92.96\,\text{mas}$, $\mu_\alpha = -226.04\,\text{mas/yr}$, $\mu_\delta = 354.98\,\text{mas/yr}$
- Use Gaia astrometry to predict coordinates for the VLBI observation/correlation
- Use the predicted position as the correlator phase center
- All processing/calibration done in ParselTongue (Python/AIPS) and AstroPy



EB081 Preliminary Results

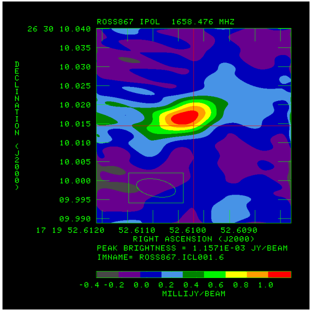
EB081a
June 2020



Stokes I: 0.82 mJy

Stokes V: 0.53 mJy (+65%)

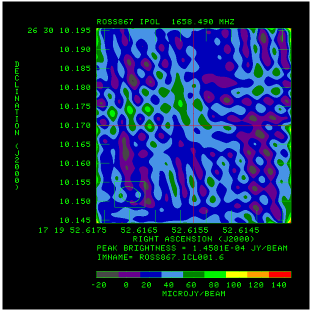
EB081b
November 2020



Stokes I: 1.2 mJy

Stokes V: 0.84mJy (+73%)

EB081c
March 2021



No Detection

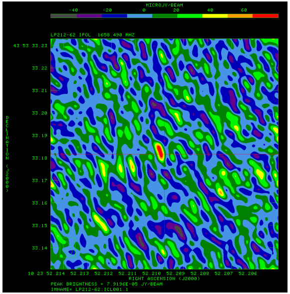
- Ross 868: No detection in any epoch.

Stellar Systems detected in LoTTS

"The Population of M dwarfs observed at low radio frequencies", Callingham e.a., Nat. Astr.

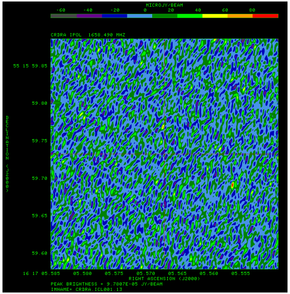
Goal: Pilot to test EVN detection on 3 selected sources, compare optical vs. radio emission region, measure polarization and variability.

LP 212-62: M5.0V, 18.2 pc
Brightest RS in LoTTS



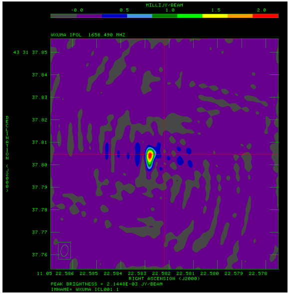
I: 0.08 mJy (6σ), V: -75%

CR Dra: M1.5Ve binary, 20.1 pc
Close double (0.9 day, 0.2")



Not Detected

WX UMa: M6.0V, 4.9 pc
Nearby, high magnetic field



I: 2.14 mJy, V: -68%, 6.5 mas offset

Astrometric follow-up on WX UMa: 3 epochs, 2 observed, both non-detections.