High-resolution, wide-field Mapping of SNR Cassiopeia A

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Collaborators

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Cassiopeia A

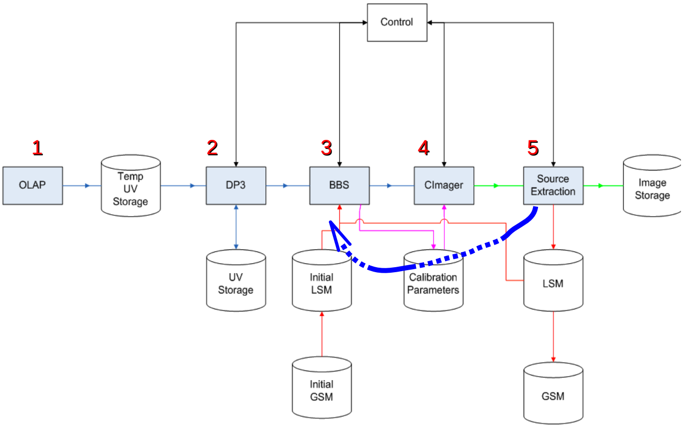
- Supernova remnant, central X-ray source, decaying flux
- A-team source: the brightest radio source in LOFAR sky

LOFAR Fundamentals

- **LBA:** $10-90$ MHz; **HBA:** $110-250$ **MHz.**
- **Baselines:** **CS** $\lesssim$ 2km; **RS** $\lesssim$ 70 km; **EU** 400 km.
- **Bandwidth:** ~ 47.5 MHz; **Resolution:** $\tau \sim 1$s; $\delta\nu \lesssim 1$kHz.

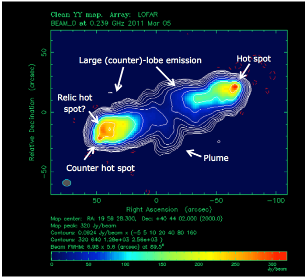
- Data stored on cluster; processed using imaging pipeline tools.

LOFAR Imaging Pipeline

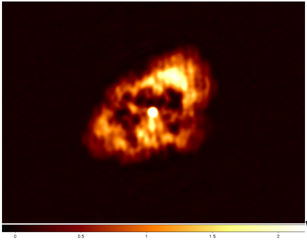


- LBA calibration: challenging; solve for A-team sources.

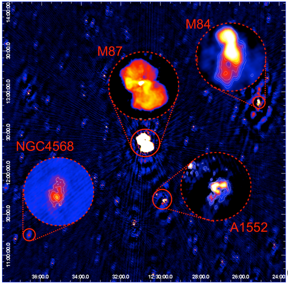
A-team Sources



McKean



Wucknitz



Gasperin

CAS-A??

Our Observations

LBA/ HBA observations:

- Long runs to detect spectral lines
- Raw data with 1-second time interval (15/18 hours)
- Frequency resolution : $\sim$ 360, 762 or 3100 Hz.
- RS stations are critical to construct good sky models.

Goals

- Make deep, wide-field images of Cas-A in continuum.
- Detect radio recombination lines using Cas-A as a background source.

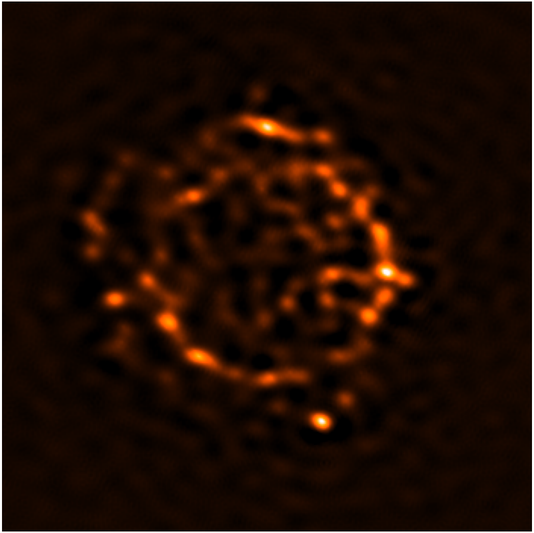
Processing

- NDPPP : interference rejection
- Average data for continuum imaging:
  - LBA 5-second interval, 16 channels/SB;
  - HBA3-second interval, 4 channels/SB

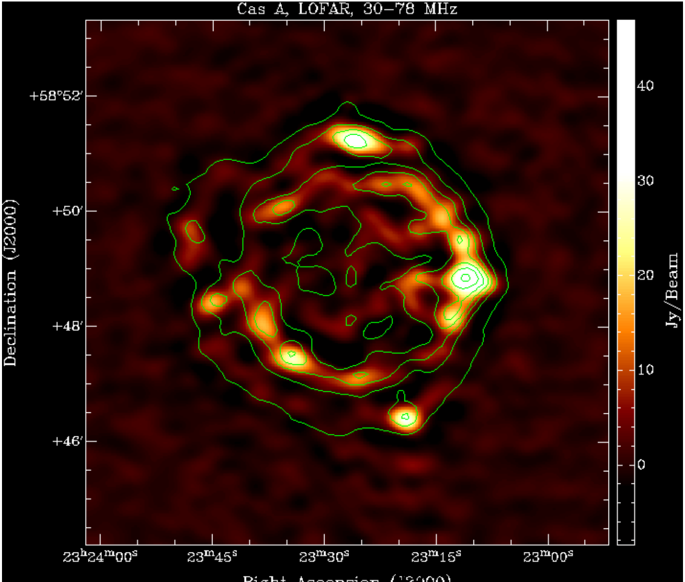
- Calibrate using earlier sky models (BBS, shapelets)
- Average data to 1 channel/SB - reduces size considerably !
- **Calibrate for DDEs using Sagecal** (Kazmi et al. 2010)
- Make image $\Rightarrow$ source model
- Repeat calibration

- **For RRLs** : calibrate full-res data and make channel maps.

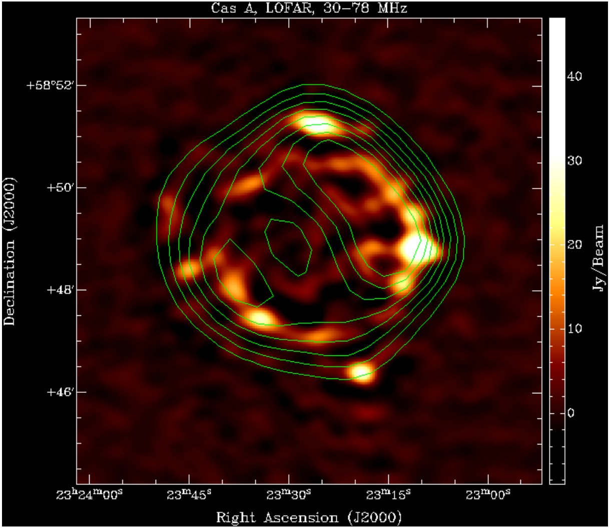
LBA Continuum Map 30-78 MHz



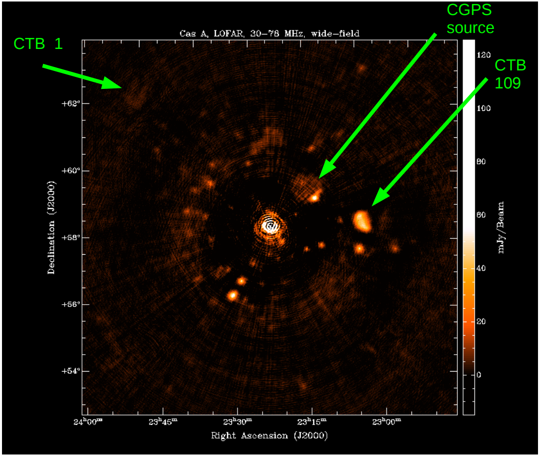
VLA - 1.3 GHz map contours



VLSS - 74 MHz contours



LBA background-sources map



RRLs: What Are They?

- Ionized gas (of species X) emits recombination lines

$$\nu = Z^2 R_X c \left(\frac{1}{n^2} - \frac{1}{(n+\Delta n)^2} \right)$$

- Natural widths $\ll$Doppler broadening: Gaussian

$$\phi(\nu) = \frac{2}{\Delta\nu_D} \sqrt{\frac{\ln(2)}{\pi}} \cdot e^{-4\ln(2)(\nu-\nu_0)^2/\Delta\nu_D^2} \quad (\mathrm{Hz}^{-1})$$

- When collisions become important: Voigt

$$\phi(\nu) = \frac{2}{\Delta\nu_D} \sqrt{\frac{\ln(2)}{\pi}} \cdot \mathrm{H}\left(\sqrt{\ln(2)}\frac{\Delta\nu_L}{\Delta\nu_D}, 2\sqrt{\ln(2)}\frac{\nu-\nu_0}{\Delta\nu_D} \right) \quad (\mathrm{Hz}^{-1}).$$

- Typical widths range $30-70\,\mathrm{km/s}$
- Emission or absorption: depends on radio frequency of observation

Why Observe RRLs?

- Trace HII regions: differentiate between thermal & non-thermal gas
- Distribution of electron temperature and abundance gradients
- Carbon RRLs & PDRs
- Diffuse ionized gas: disk-halo models
- **Foregrounds for deeper extra-galactic surveys**

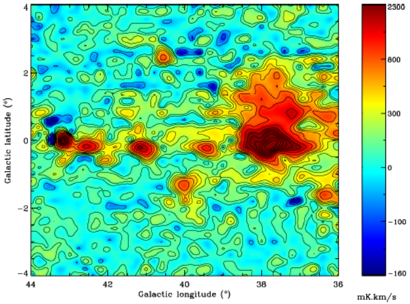
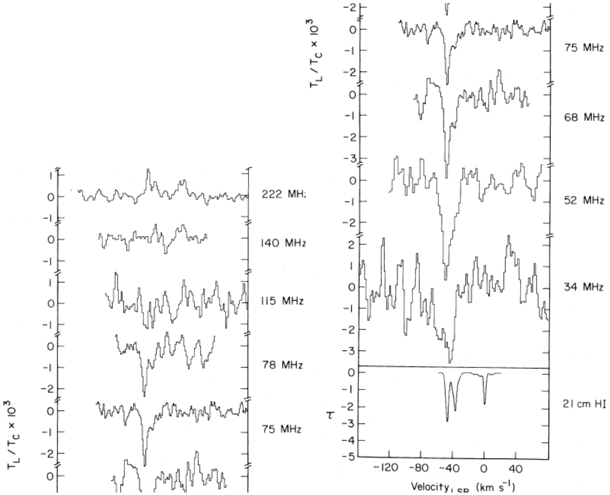


Figure 6. Map of the total integrated RRL emission (in mK km s^{-1}) at a resolution of 15.5 arcmin. The integration is made between −20
The contours are the same as in Fig. 4, where the value 5.29 K km s^{-1} is the peak of the line integral in this map.

Alves et al. 2010

Parkes ZOA - RRLs

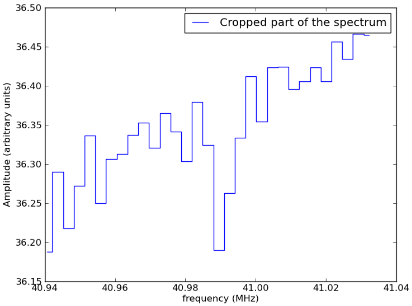
RRLs towards Cas-A

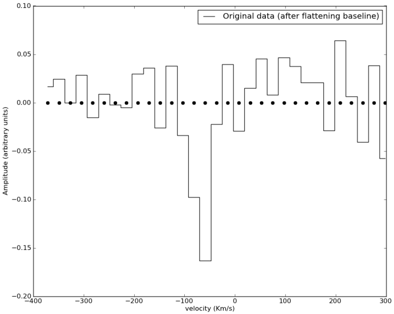


(Payne et al. 1989)

RRL Detection

C543α, **40.98 MHz** :$\sim$ 15 Hours, 3 KHz

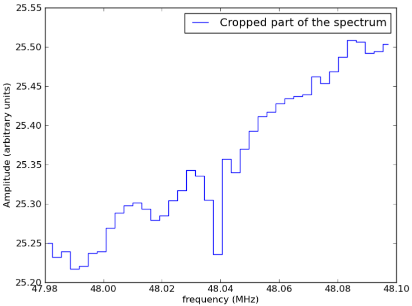


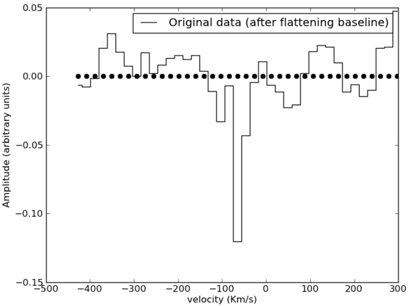


Note: No "online" doppler tracking.

RRL Detection

C515α, **48.028 MHz** :$\sim$ 15 Hours, 3 KHz

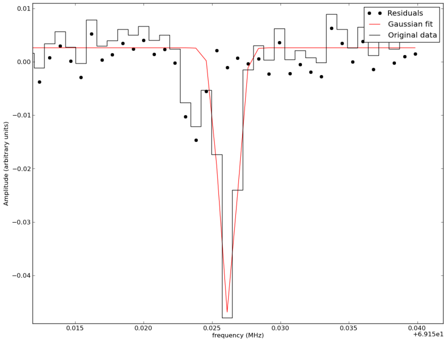


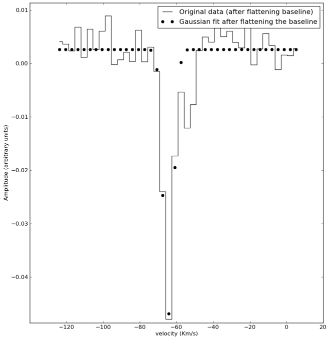


Note: No "online" doppler tracking.

RRL Detection

C456α, **69.2 MHz** :$\sim$ 18 Hours, $\sim$ 760 Hz





Note: No "online" doppler tracking.

Summary

- LOFAR can make wide-field, high-resolution images at lowest frequencies.
- Challenges for calibration and imaging.
- We have succeeded in detecting RRLs at various frequencies in $30-78$ MHz band.

- Outlook
  - Catalog of RRLs using LOFAR
  - Maps of Cassiopeia A in RRL channels.
  - Proposed RRL surveys with LOFAR.

Acknowledgements

- LOFAR hardware / software engineers
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- Radio Observatory & science support staff.