A multifaceted study of the Lockman Hole region: from HI to LOFAR

Raffaella Morganti
ASTRON (NL) and Kapteyn Institute (Groningen)

with the major contribution from: I. Prandoni, G. Guglielmino, K. Gereb, E. Mahony, I. van Bemmel

ASTRON is part of the Netherlands Organisation for Scientific Research (NWO)
Deep fields/surveys in Ger’s career …..

work of Arno Schoenmakers, Ger, Emanuela Orru +

Many science goals can be covered …..
Faint (sub-mJy) radio population, their spectral index and the HI content

- Nature and properties of the faint radio population: AGN vs SF
- Relevance of faint radio AGN for feedback
- Gas content (for the low redshift z < 0.1 population)
The Lockman Hole: faint radio population, their spectra index and the HI content

- Nature and properties of the faint radio population: AGN vs SF. Relévance of faint radio AGN for feedback.

- From recent studies:
  - High frequencies: Flatter spectral indices and larger dispersions at high frequencies (from 1.4 to 20 GHz) at sub-mJy radio fluxes, suggesting that core-dominated AGN are playing a key role in the sub-mJy radio population. [e.g. Prandoni+ 2006, Whittam+ 2012]
  - Low frequency studies (0.3 – 0.6 – 1.4 GHz): important for investigating the presence of synchrotron self-absorbed mechanism. Existence of flattening is controversial. Flattening more significant for compact (<3") sources. optically thin (steep spectrum) or self-absorbed (flat spectrum) synchrotron emission.
The Lockman Hole: faint radio population, their spectra index and the HI content

- Nature and properties of the faint radio population: AGN vs SF. Relevance of faint radio AGN for feedback.

- Gas content (for the low redshift z < 0.1 population)
  
  - Multi-wavelength information and radio spectral indices to constrain the origin of the radio emission in sub-mJy radio sources. Importance of very low frequencies (30-200 MHz), where self-absorption phenomena are expected to be very important.

  - Use the broad band @21cm to extract HI spectra and do stacking => derive the HI content of galaxies with z up to 0.1, compared to their optical and radio properties (using SDSS spectra)

- Field of choice: Lockman Hole
  => high Dec (ideal for WSRT and LOFAR observations), a lot of ancillary data .....

- Observations: WSRT 1.4 GHz (160 MHz, covering redshift range 0 - 0.1) and 325 MHz LOFAR 150 MHz (commissioning & Cycle 0), 60 MHz (Cycle 0)
16 pointings (6.6 sq.degr.)

rms ~11 µJy (central 2 sq deg)

About 6000 sources with S>55 µJy

Source counts complete down to 70-80 µJy

Guglielmino, Prandoni, Morganti, Rottgering, Jarvis, Garrett 2013, A&A in prep
Lockman Hole region
WSRT Mosaic @ 1.4 GHz

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A&A in prep
Largest field imaged at such depth

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The Lockman Hole Region @ 345 MHz

WSRT 345 MHz observations in February 2012

Due to limited resolution (~40x70 arcsec) → confusion-limited image at a level of rms~0.7-0.8 mJy). Catalogue:
334 sources, complete down to 4.8 mJy (~3-4x deeper than WENSS).
Lockman Hole with LOFAR

Lofar commissioning => 6 hrs obs.

150 MHz Image (inner 2 sq. degr., 8"x4") from 60 of the 120 SBs.
3C244.1 subtracted
rms noise → 1.5 mJy

152 sources extracted in the 1.4 GHz mosaic region (5σ).
Several counterparts of brightest WSRT 1.4 GHz sources are clearly visible.

First full resolution image of a deep field
Guglielmino 2013 PhD thesis
Radio spectra are consistent with single power laws

→ no significant spectrum curvature (< C > ~ 0), at least down to 150 MHz

→ If self-absorption effects are in place, not very compact sources (>10 kpc)!

This study (from commissioning data) is still limited to the strongest sources....
Spectra index analysis: radio color-color plots (150 - 345 vs 610 -1400 MHz)

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Status of the New LOFAR data (Cycle 0) (150 and 60 MHz)

**HBA**: reduction in progress
=> 10SB, rms ~2mJy/b,
19x16” Peeling of 3C244.1 still to be improved

**LBA**: reduction in progress
more problems with ionosphere

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**Area of the Lockman Hole (Mahony et al. in prep)**

- Abell 1132
- 1029+570 > 2 Mpc

**Tuesday, 5 November 13**
Cold gas (HI) plays an important role in the formation and evolution of galaxies

Main goals:
- Investigate relations between HI properties and other characteristics of the host galaxy (color, emission lines, SF & radio AGN properties)
- Evolution with redshift: Stacking gives the opportunity to investigate the global HI properties beyond $z = 0$ with today telescopes

Preparation for higher-redshift HI surveys (Apertif, ASKAP, MeerKAT...)

## Stacking in the LH field: piggyback from the continuum observations

WSRT observations using 160 MHz band (1300 - 1460 MHz), 1024 chans
=> coverage 0<z<0.09, velocity resolution 60 km/s

We use the HI spectra for stacking:
z < 0.09

Cross-correlation with SDSS spectroscopic catalog:
120 sources in total, 50 sources with radio continuum, IR Spitzer data

### Noise level:
- initially ~ 0.150 mJy/beam/chan
- after stacking ~ 20 µJy

$$M_{\text{HI}}/L_r (M_{\odot}/L_{\odot})$$
- Blue: $\sim 0.4$
- Red: $\sim 0.1$
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• after stacking \( \sim 20 \mu\text{Jy} \)

\( M_{\text{HI}} / L_r \)
\( (M_{\odot} / L_{\odot}) \)

\( g - r < 0.7 \)
\( g - r > 0.7 \)

\( 0.06 < z < 0.09 \)

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Radio sources and stacking

- Inactive (in terms of optical emission lines) galaxies are not detected in HI
- To first order (and for the low redshift range) => for the majority of radio LINERs, the radio emission seems to be connected with SF
- But: two groups based on 24 µm emission properties (tracer of the warm dust component associated with current star-formation in galaxies) => LINERs detected at 24 µm show relatively large amounts of HI, no detection for the other group

- No powerful AGN in our sample
- Radio sources in the IR inactive region are the best candidates for hosting low-luminosity radio AGN
Conclusions and future perspectives

LH region: 3 new radio catalogues obtained: 1.4 GHz, 345 MHz and 150 MHz.

No significant curvature found in the source spectra down to 150 MHz => (bright) sources analised so far have sizes >10 kpc.

=> Analysis to be extended to lower flux and frequency with Cycle 0 and new Cycle 1 observations (LBA and HBA).

[+ extensive multi-waveband information (optical/IR, MIR/FIR), photo-zs and galaxy types]

Piggyback HI stacking => feasibility proved (Gereb et al. 2013) => approach could become standard in all future radio surveys at L-band

- For the majority of radio LINERs (and for SF galaxies), the radio emission appears to be connected with star formation
- Radio sources in the IR Inactive region (no 24 µm and HI detection) are the best candidates for hosting low-luminosity radio AGN => to be confirmed with high resolution data

=> Analysis extended to larger sample (including Galex data) and results so far confirmed