The Physics of the CNM:

J B R Oonk (ASTRON, Leiden)

(1) Interstellar medium
(2) Recombination lines
(3) LOFAR & SKA1-LOW

LOFAR: Cassiopeia A (60 MHz, 10")

J. B. R. Oonk (ASTRON, Leiden)

Carbon RRL (n=576)

SKA SICILY 13/06/2014
Galaxy evolution is driven by (SF) recycling of ISM

=> What is the role of the atomic CNM?

HI em (contaminated), HI abs (difficult)
Outstanding questions.

“Galaxy evolution is driven by recycling of the ISM”

but,

what is the role of the cold atomic gas in galaxy evolution?

In particular:

- What is its morphology, dynamics and how does this compare to molecular, starforming & hot gas?
- What is its thermal, pressure balance?
- What is its ionization rate?
- What is its chemical enrichment?
- What is the CNM fraction of the HI 21 cm signal?
Diffuse RRL's \( \leq 1 \text{ GHz} \)

- RL: “ions recombining with electrons”

- Classical \((\text{Palmer & Zuckerman 1966})\)
  > 1 GHz (H, He RRL) “HII regions”

- Diffuse \((\text{Konovalenko & Sodin 1981})\)
  < 1 GHz (H, C RRL) “CNM / PDR”
  \(T_e \sim 10-300 \text{ K}, n_e \sim 0.01-1.0 \text{ cm}^{-3}\)
  - weak: \(\tau_{\text{peak}} \sim 10^{-4} \text{ to } 10^{-3} \) (MW)
  - many: 500 \(\alpha\) lines (LOFAR)
  - measure: \(\tau, v, \Delta v\)
  - derive: \(T_e, n_e, EM, \zeta(\text{H}), [\text{C/H}]\)
Models: Line width & Optical depth

\[ \Delta V_T = \Delta V_D + \Delta V_P + \Delta V_R \]

\[ \Delta V_P \sim \left( n_e n^{5.2} \right) / \left( T_e^{1.5} \nu \right) \]

\[ \Delta V_R \sim \left( T_R n^{5.8} \right) / \nu \]

\[ \tau_C \sim T_e^{-5/2} \ E M_C \left( b_n \beta_n \right)_C \]

* RRL can disentangle the CNM & WNM of HI 21 cm

(Salgado et al. in prep.)

J.B.R. Oonk (ASTRON, Leiden)
Returning to the BIG question.

“Galaxy evolution is driven by recycling of the ISM”

but,

what is the role of the cold atomic gas in galaxy evolution?

Method:

- Localize the (C)RRL gas & compare with CO, HI and HII.
- Thermal properties of RRL gas ($T_e, n_e, EM$)
- Ionization rate of the RRL gas ($\zeta_H$)
- Carbon abundance ($[C/H]$)
- Kinematics of the RRL gas ($\nu, \Delta\nu$)
RRL Surveys

The Power of LOFAR:

*Sensitivity, Resolution, FoV, BW*

=> “Survey speed” \((\alpha, \delta, \lambda)\)

LBA 10 - 70 MHz : 400 RRL \(\alpha\)-lines
HBA 105 - 250 MHz : 100 RRL \(\alpha\)-lines

A) Medium resolution Galactic survey

*From degree-scales to >10'-scales*

B) Galactic pinhole survey

*Adding the <10'-scales*

C) Extragalactic survey

*The extragalactic (C)RRL universe*

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A: Galactic diffuse RRL's: All that was known so far

(Kantharia & Anantharamaiah 2001)

Major issues:

(1) Beam FWHM > 2 deg. (unresolved clouds / dilution)

(2) Resolution mismatch (spatial & spectral)

(3) Limited frequency coverage

Data:

* 328 MHz, Anantharamaiah (1985)

* 76 MHz, Erickson et al. (1995)

* 34 MHz, Kantharia & Anantharamaiah (2001)
A: LOFAR Galactic RRL Survey

Preliminary (LBA 6 stations):

→ CRRL wide spread in Galactic plane
→ τ, Δv decrease with distance from GC

J.B.R. Oonk (ASTRON, Leiden)
**B:** Galactic pinhole RRL's (all that was known so far)

Cas A issue: resolution mismatch (Kantharia+1998)

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(LBA: 400 $\alpha$ lines)
(HBA: 80 $\alpha$ lines)
B: Cas A (33-56 MHz)

Integrated $\tau$ varies over the supernova remnant (agrees with HI)

$\Rightarrow$ Integrated $\tau$ peaks on the western hotspot

(Oonk+)

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B: LOFAR Cas A - CNM Hydrogen ionization rate

a) \( \zeta_H [s^{-1}] \sim (\tau_{Hn} / \tau_{HI}) \times (T_e / T_s) \times (T_e / [b_n \beta_n]_H) \)  

b) \( \zeta_H [s^{-1}] \sim (\tau_{Hn} / \tau_{Cn}) \times (n_e / T_e^{0.5}) \times ([b_n \beta_n]_C / [b_n \beta_n]_H) \)

(Shaver 1976)  
(Smirnov+Sorochenko 1990)

WSRT 350 MHz (12 hr, 20L)                      HBA-HIGH 225 MHz (3 hr, 6L)

Cassiopeia A (1.0 km/s channels)

HBA-HIGH 225 MHz (3 hr, 6L)

H(Per-1)  C(Per-1)  C(Per-2)  C(Orion)  H(Per-2)  H(Orion)

HBA-HIGH 225 MHz (3 hr, 6L)

H(Per-1)  C(Per-1)  C(Per-2)  C(Orion)  H(Per-2)  H(Orion)

=> LOFAR HBA & RRL's: ionization rate in CNM

\( \zeta_H = 1 \times 10^{-16} [s^{-1}] \)

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B: LOFAR Galactic pinhole studies

Cygnus A (bright, extragalactic source; Oonk et al. 2014)

Measurements:

- $\tau_{\text{PEAK}} = 2 \times 10^{-4}$
- $v_{\text{LSR}} = +4$ km/s
- FWHM = 10 km/s

Derived properties:

- $T_e = 110$ K
- $n_e = 0.06$ cm$^{-3}$
- $\text{EM}_\text{C} = 0.001$ cm$^{-6}$ pc
- $[\text{C}/\text{H}] = 1.8 \times 10^{-4}$
- $\zeta_\text{H} < 4 \times 10^{-16}$ s$^{-1}$

LOFAR-LBA (10h)

- $BW = 33-57$ MHz
- $\Delta f = 0.4$ kHz
- $\Delta v = 2-4$ km/s

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M82 LOFAR LBA (60 MHz)
First extragalactic CRRL

Peak: -0.0028
Centroid: 211.34 km s\(^{-1}\)
FWHM: 30.65 km s\(^{-1}\)

(Morabito+ in prep.)
SKA1-LOW: Galactic

(10-100) x LOFAR !!

(LOFAR RRL universe)

- LOFAR (north) : scales > 10' for $N(\text{HI}) > 3 \times 10^{20} \text{ cm}^{-2}$
- SKA1-LOW (south) : scales > 3' for $N(\text{HI}) > 5 \times 10^{19} \text{ cm}^{-2}$

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SKA1-LOW: Extragalactic

* Dramatic increase in (RRL) sources:

LOFAR \( (7.0 \text{ Jy}) \sim 10^2 \)

SKA1-LOW \( (0.4 \text{ Jy}) \sim 10^5 \)

(RRL comb: \( z \) determination)

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SKA1-LOW: RRL pinhole studies

MW Pinhole: SKA1-LOW ~ LOFAR x 1000 !! (W3,4,5 example)

N(S, LOFAR) < 0.01 / deg$^2$

N(S, SKA1-LOW) > 3 / deg$^2$

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SKA1-LOW: Nearby galaxies

SKA1-LOW (3πsr, 8h pointings)
- 500 nearby SF galaxies
- 25 percent spatially resolved
- intermediate absorbers

Starforming galaxies

Distance [Mpc] vs SFR [Msun/yr]

60 MHz
160 MHz
220 MHz

(long baselines necessary to locate CRRL regions)

M82 (LOFAR 140 MHz: 6")

Toribio, Adebahr & Varenius

J.B.R. Oonk (ASTRON, Leiden)

SKA SICILY 13/06/2014
Conclusion: CRRL $\rightarrow$ CNM ($T_e, n_e, EM, \zeta_H, [C/H]$)

LOFAR

*Milky Way* $\geq 10', N(\text{HI}) > 3 \times 10^{20} \text{ cm}^{-2}$
*Extragal.* $\leq 300$ sources

SKA1

*Milky Way* $\geq 3', N(\text{HI}) > 5 \times 10^{19} \text{ cm}^{-2}$
*Extragal.* $\geq 100000$ sources

$\Rightarrow$ “Frequency resolution” (crucial)
RRLs and more ISM @ low frequencies

(0) C and H RRL's trace the CNM
(1) Thermal absorption (ionized gas)
(2) Masers (ex. OH 55 MHz: Hoffman+)
(3) Redshift determination (CRRL)
(4) HI absorption at z > 3
(5) Pulsars
(6) Epoch of Reionization (EoR 1)
   - RRL foregrounds
(7) Epoch of Recombination (EoR 2)
   - HRRL masers
(8) Serendipity ...

LOFAR-LBA (55-60 MHz)
IC443 (Galactic SNR)
FWHM ~ 25"
Image ~ 1x1 deg²
courtesy,
G. White & J. Gregson

J.B.R. Oonk (ASTRON, Leiden)
SKA1-LOW: Transformational for RRL's

Galactic: SKA1-LOW > LOFAR x 10 !!

<table>
<thead>
<tr>
<th>Frequency [MHz]</th>
<th>FWHM [arcmin]</th>
<th>SKA1 $T_{RMS}$ (1 kHz, 8h, 9L) [mK]</th>
<th>SKA1 $\tau_{peak,5\sigma}$ $\times 10^{-4}$</th>
<th>LOFAR $\tau_{peak,5\sigma}$ $\times 10^{-4}$</th>
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<tbody>
<tr>
<td>60</td>
<td>8.6</td>
<td>980</td>
<td>(0.5-0.05)</td>
<td>[5.0]</td>
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<tr>
<td>160</td>
<td>3.2</td>
<td>138</td>
<td>(1.0-0.10)</td>
<td>[3.3]</td>
</tr>
<tr>
<td>220</td>
<td>2.3</td>
<td>138</td>
<td>(2.1-0.21)</td>
<td>[5.0]</td>
</tr>
<tr>
<td>350</td>
<td>1.5</td>
<td>154</td>
<td>(7.5-0.75)</td>
<td>–</td>
</tr>
</tbody>
</table>

Table 1: Galactic RRLs with the SKA1-LOW core. Column (1) Observing frequency. Column (2) Beam FWHM for the SKA1-CORE with a 2 km diameter. Column (3) SKA1-LOW core $T_{RMS}$ value, as obtained from the SKA1-ISP document, for an effective baseline $B_{eff}$=2 km for 1 kHz channels, 8h observing time and stackign 9 lines. Column (4) the 5σ peak optical depth limit for 1 kHz channels, 8h observing time and stacking 9 lines. These optical depth limits correspond to the inner Galactic plane for continuum temperatures between 140 and 1400 K at 408 MHz (Haslam et al. 1982). These the 408 MHz values are scaled to the observing frequencies with a $\lambda^{2.5}$ scaling (Rogers et al. 2008). Column (5) Representative, observed LOFAR core (2 km diameter) 5σ peak optical depth values, for 1 kHz channels, 8h observing time and stacking 9 lines. This shows that the SKA1-LOW core is about an order of magnitude more sensitive than the LOFAR core.

- LOFAR (north) : scales > 10' for $N(\text{HI}) > 3 \times 10^{20}$ cm$^{-2}$
- SKA1-LOW (south) : scales > 3' for $N(\text{HI}) > 5 \times 10^{19}$ cm$^{-2}$
### Extragalactic: SKA1-LOW > LOFAR x 10 !!

<table>
<thead>
<tr>
<th>Frequency [MHz]</th>
<th>LOFAR (30 km/s, 8h) [Jy]</th>
<th>SKA1 (30 km/s, 8h) [Jy]</th>
<th>SKA1 3πsr (30 km/s, 2 yr) [Jy]</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>170</td>
<td>1.94</td>
<td>2.34</td>
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<tr>
<td>160</td>
<td>7</td>
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<td>0.59</td>
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<tr>
<td>220</td>
<td>11</td>
<td>0.24</td>
<td>0.89</td>
</tr>
<tr>
<td>350</td>
<td>-</td>
<td>0.19</td>
<td>1.25</td>
</tr>
</tbody>
</table>

**Table 2:** Extragalactic RRLs. LOFAR and SKA1-LOW limiting source flux $F_{v,lim}$ for a $5\sigma$ (8 hr, stacking 9 lines) detection of $\tau_{peak}=10^{-3}$. Column 2 gives the LOFAR $F_{v,lim}$ for a single pointing 8 hr observation and stacking 9 lines. Similarly column 3 gives the SKA1-LOW $F_{v,lim}$ for a single pointing 8 hr observation and stacking 9 lines. Column 4 gives SKA1-LOW $F_{v,lim}$ for the 2 yr survey outlined in the SKA1-ISP document upon stacking 9 lines. A velocity resolution of 30 km s$^{-1}$ and a 200 arcsec Beam FWHM is assumed in all cases. The LOFAR limiting flux values are obtained from LOFAR cycle 0 observations by our group.

- **LOFAR** (north) : “3C limit”
- **SKA1-LOW** (south) : “7C limit”
RRL models: Line width broadening

Total (solid) width

Contributions:

1. Doppler (dash)
2. Pressure (dash-dot)
3. Radiation (dash-dot-dot)

\[ \Delta V_p \sim (n_e n^{5.2}) / (T_e^{1.5} \nu) \]
\[ \Delta V_R \sim (T_R n^{5.8}) / \nu \]

\( [N(HI) = 10^{20} \text{ cm}^{-2}] \)
RRL models: Integrated Optical Depth ($\tau$)

Phases:

**CNM (atomic):**
- $n_e = 0.05 \text{ cm}^{-3}$
- $T_e = 100 \text{ K}$

**WNM:**
- $n_e = 0.01 \text{ cm}^{-3}$
- $T_e = 10^4 \text{ K}$

**HII:**
- $n_e = 300 \text{ cm}^{-3}$
- $T_e = 10^4 \text{ K}$

* i.e. RRL can disentangle CNM, WNM in HI 21 cm

$$\tau_c \sim T_e^{-5/2} E M_c \left( b_n \beta_n \right)_c$$

$[N(\text{HI})=10^{20} \text{ cm}^{-2}]$

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