Extragalactic Radio Continuum Observations with the Effelsberg 100-m Telescope: Total Intensity and Linear Polarization

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- Observations & data reduction and analysis software
- Single extended objects
- Galaxy samples
Receivers in **secondary** focus

21 cm receiver in **primary** focus
# Continuum Receivers with Polarimeter

<table>
<thead>
<tr>
<th>λ</th>
<th>frequency band</th>
<th>$T_{sys}$</th>
<th>HPBW</th>
<th>no.horns</th>
<th>location</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.8 cm</td>
<td>10.3 – 10.6 GHz</td>
<td>50 K</td>
<td>69 &quot;</td>
<td>double</td>
<td>SF</td>
</tr>
<tr>
<td>3.6 cm</td>
<td>7.8 – 8.9 GHz</td>
<td>22 K</td>
<td>83 &quot;</td>
<td>single</td>
<td>SF</td>
</tr>
<tr>
<td>6.2 cm</td>
<td>4.6 – 5.1 GHz</td>
<td>27 K</td>
<td>146 &quot;</td>
<td>double</td>
<td>SF</td>
</tr>
<tr>
<td>11 cm</td>
<td>2.2 – 2.3 GHz</td>
<td>17 K</td>
<td>275 &quot;</td>
<td>single</td>
<td>SF</td>
</tr>
<tr>
<td>21 cm</td>
<td>1.3 – 1.7 GHz</td>
<td>20 K</td>
<td>580 &quot;</td>
<td>single</td>
<td>PF</td>
</tr>
</tbody>
</table>

Broad-band receiver (C-band) with spectro-polarimeter:

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<th>λ</th>
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<th>location</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.5 cm</td>
<td>4.0 – 9.3 GHz</td>
<td>27 K</td>
<td>102 &quot;</td>
<td>single</td>
<td>SF</td>
</tr>
</tbody>
</table>
Radio continuum observations

On the fly observations
(of extended sources)

Observing cycle of 64 ms

\[
\text{CAL: linearly polarized noise diode}
\]

- \( S/\text{CAL} = I \) (radio intensity)
- \textbf{Polarization} as reference for observed polarization angle
- A time signal sets the phases

Up to 30 coverages needed!

Emerson & Gräve, 1988
Data Reduction

**NOD2** (Haslam 1974), written in Fortran, NOD2 input format

**NOD3** (Müller, Krause, Beck, Schmidt 2017):

Graphical User Interface supported software package for radio continuum and polarization observations

- Written in **Python**, input map format is **FITS**.
- Designed to **reduce** and **analyze** single-dish maps → **final maps** in total intensity and linear polarization.
- Especially powerful to **remove 'scanning effects'** due to clouds, receiver instabilities and RFIs with e.g. revised
  - -- **basket weaving**
  - -- **restoration** for dual beam observations
  - -- **flatten**
- **Combination** of single-dish with interferometer data in the map plane.
- Offers an improved method for the **bias correction** of **PI maps**.
- Can include special tasks written by the individual observer.
- Is extendable to multichannel data (**data cubes**) in Stokes I, Q, U.
- Is available under **open source license** GPL for free use.
Comparison NOD3 with NOD2 for restauration

Restauration in NOD2: Emerson et al. 1979
Dual beam observations at 6.2cm, single coverage, horn1 and horn2

Müller et al. 2017
Examples of map analysis with NOD3

Strip integration of edge-on galaxies: Task Box Models

\[ i = 86^\circ \]
\[ \text{p.a.} = 50^\circ \]
\[ \sigma = 9 \mu \text{Jy/b.a.} \]
\[ \text{width} = 36'' \]
\[ \text{height} = 4'' \]
19 boxes

Müller et al. 2017
Examples of map analysis with NOD3

Integration of **galaxy segments** in face-on view: Task Galaxy Segments

Same sectors, different ring width

Same ring widths, different sectors

Müller et al. 2017
Combination of single-dish with interferometer maps

NGC 891  C-band  VLA  Effelsberg

NGC 4631  C-band

NOD3 (ImMerge): red contours
CASA (Feather): black contours
AIPS (IMERG): white contours
18" HPBW

Mora, Krause et al. in prep.

Müller et al. 2017

combined map with NOD3 in the map plane
Maps of single objects
as observed with the Effelsberg 100-m telescope
Radio relics at the peripheries of galaxy clusters

IRXS 06+42 (Toothbrush) $z = 0.225$ $90'' \approx 330$ kpc

$\sigma_I = 0.5$ mJy/beam, $\sigma_{UQ} = 0.13$ mJy/beam

- $P$ up to 50%
- Magnetic field ordered over several Mpc

$1' \approx 220$ kpc
$5' \approx 1$ Mpc

Kierdorf et al. 2017
CIZA J2242+53 (Sausage), \( z = 0.192 \)

\[ \begin{align*}
\text{3.6cm} & \quad 1.5' \text{ HPBW (300 kpc)} \\
\text{6.2cm} & \quad 2.45' \text{ HPBW (480 kpc)}
\end{align*} \]

\[ \sigma_I = 0.4 \text{ mJy/beam} \]
\[ \sigma_{UQ} = 0.07 \text{ mJy/beam} \]

\[ \sigma_I = 0.8 \text{ mJy/beam} \]
\[ \sigma_{UQ} = 0.12 \text{ mJy/beam} \]

1' \approx 195 \text{ kpc}

5' \approx 1 \text{ Mpc}

Kierdorf et al. 2017
Single-lobed (FR II) radio galaxy CGCG049-033

8.35 GHz TP + B

8.35 GHz PI + B

RM (20cm NVSS/3.6cm)

84ʺ HPBW (70 kpc)

- BH > 10⁹ M☉, P = 20-50%
- Projected jet length ≈ 440 kpc with a toroidal magnetic field
- Counterlobe is undetected down to brightness contrast of ≈ 10

Bagchi et al. 2007
Nearby spiral galaxies as observed with the Effelberg 100-m telescope and their magnetic fields
M31 6.3cm B-vectors 3' HPBW (700 pc) D = 0.8 Mpc

Total intensity

Polarized intensity

Gießübel, PhD 2013
IC342  6.3cm  B-vectors  3' HPBW (2.7 kpc)  D = 3.1 Mpc

Total intensity

Polarized intensity

Axisymmetric spiral magnetic field (ASS)
along the disk plane  (Krause et al. 1989)
Spiral galaxies seen edge-on

NGC 891 \(i \approx 90^\circ\)

NGC 4631 \(i \approx 89^\circ\)

intrisic magnetic field orientation

Effelsberg 3.6cm 84'' HPBW

rms (U, Q) = 70 \(\mu\)Jy/beam
Face-on galaxies show a **spiral magnetic field (ASS)** along the disk → disk-parallel field in edge-on galaxies, plus **X-shaped field in the halo**

**Magnetic field strength** in the **halo** comparable to **disk** field strength
A **dynamo generated** large-scale magnetic field in the disk

→ **ASS disk-field**

Large-scale RM-pattern indicates an **ASS disk-field**. Its poloidal component alone cannot explain the observed halo fields.

→ **dynamo action in the halo**

or

**galactic wind needed**

courtesy to R. Beck
Global galactic-scale MHD simulations of the CR-driven dynamo (Hanasz et al. 2009):

- horizontal spiral field also in the halo?
- large lobes of field in vertical direction?
- small-scale (turbulent) fields?

→ X-shaped field structure

Importance of **galactic wind:**

**Vertical transport of magnetic flux and helicity**
Are halo magnetic fields coherent or ordered?

3.6 cm Eff.  84" HPBW

coherent  ordered

courtesy A.Fletcher

- Both fields give linearly polarized intensity
- Only a coherent field yields a net Faraday rotation, hence significant RM

**Rotation measure**: observations at > 2 frequencies needed or **RM synthesis** (broad band receiver & polarimeter needed)
**NGC4631**

**Effelsberg 3.6cm 84″**

**VLA C-band 20″**

Eff & VLA merged only in total power, NOT in polarization

**RM(6cm merg + 3.6cm Eff)**

**RMsynthesis C-band VLA**

First evidence for a **coherent, large-scale magnetic field in the halo**

⇒ Helical field?

Mora & Krause 2013

Mora et al. in prep

⇒ **Effelsberg spectro-polarimeter needed!**
Samples of spiral galaxies

- NGC 4725 3.6cm Eff

- total intensity
- linear polarization
**KINGFISHER**: Key Insight in Nearby Galaxies Emitting in Radio

KINGFISH: 61 galaxies

KINGFISHER only with δ ≥ -21° are 50 galaxies, observed with Effelsberg
Kingfisher galaxies observed at \( \lambda \, 20 \text{ cm} \, (10), \, 6 \text{ cm} \, (35), \, \text{and} \, 3.6 \text{ cm} \, (7) \) plus archival Effelsberg data, also at \( 2.8 \text{ cm} \) 

- spectral energy distribution \( \text{SED: } \alpha_{nt}, f_{th} \) (23%@6cm, 10%@20cm)
- definition of mid-radio \((1-10 \text{ GHz}) \text{ continuum bolometric luminosity} \)

\[
\text{MRC} = \int_{1.4}^{10.5} L_\nu \, d\nu
\]

\text{MRC} \text{ is shown to be an ideal star formation tracer,}
\text{independant of dust attenuation or absorption.}

Total nonthermal spectral index is not fixed \((-1.5 < \alpha_{nt} < -0.5)\) 

\( \Rightarrow \) Influence of \textbf{star formation} on the energetics of \textbf{CRE population} and on \textbf{magnetic field strength}
Direct simulations of a SN-driven galactic dynamo (Gressel et al. 2008) indicate as well that high SFR increases $B_r$ but not $B_{\text{reg}}$ (small scale turbulent dynamo). Only turbulent magnetic field is amplified in SF regions (Schleicher & Beck 2013).
Polarimetric study of nearby and distant galaxies

Integrated values for 43 nearby spiral galaxies:
→ globally: $P$ decreases with increasing luminosity
→ higher SFR increases only $B_r$

Pilot study for 24 distant spiral galaxies with Effelsberg at 6cm, < 2.'5
- polarization detected in 14
- upper limits given for the other 10

Deep polarization surveys can detect distant unresoved spiral galaxies
Integrated polarization of spiral galaxies

Normal spirals (23)  Barred spirals (20)

\[ P \leq 20\% \text{ at 4.8 GHz, highest for } i \geq 50^\circ \]

- \( B \) is aligned with optical major axis, except for strong bars
- \( P \) depends mainly on \( B_{\text{ran}} / B_{\text{reg}} \) for \( i \leq 50^\circ \)
- Unresolved symmetric spiral galaxies behave as idealized background sources without internal Faraday rotation.

Stil, Krause et al. 2009
Conclusions

• Effelsberg 100-m telescope is best suited for radio continuum observations, also and especially in polarization.

• The new NOD3 software is an up-to-date GUI supported reduction and map analysis software package, also extendable for the coming broadband, multi-channel observations.

• Surveys of unresolved galaxies can answer important questions about the physics in galaxies.

• Sensitive linear polarization and radio continuum maps of single objects at different scales → e.g. direct comparison with dynamo theory

• Single-dish observations are necessary for the combination with interferometer maps in order to trace the extended flux density, also in linear polarization:

  These are complementary observations!

→ Broad-band receivers with spectro-polarimeter are necessary.
Thank you!