Magnetization of the IGM:
Role of Startburst Dwarf Galaxies

Amrita Purkayastha
AIIfA, Bonn

Supervisors: Uli Klein (AIIfA, Bonn)
Dominik Bomans (RUB, Bochum)

20 May 2013, IRA, Bologna
Magnetic Fields in the Universe

Observed, for e.g., in the Coma Cluster

Image: Brown & Rudnick, 2011
What's their origin?

- Primordial – complicated particle physics before the CMB!
- Biermann battery – plasma physics on small scales in the ICM.
- Processes in galactic evolution. Two mechanisms can explain the transport of magnetic fields produced in galaxies into the ICM/IGM
  - Jets and radio lobes emerging from powerful radio galaxies
  - Galactic winds from star-forming galaxies
Can Starburst Dwarfs Magnetize the IGM?


- The two prime arguments for dwarf galaxies as agents (in competition with AGNs) are:
  - Large number, predicted in ΛCDM cosmology
  - Shallow gravitational potentials, rendering outflows of hot gas and relativistic plasma feasible
Synchrotron Halos Around Dwarf Galaxies

- Hard to detect at cm wavelengths
- Characterized by a break at some frequency $v_b$
- In low frequencies, one should detect the flatter low-frequency part of the spectrum, hence find non-thermal halos wrapped around
The First Detection of a Synchrotron Halo: NGC 4449

Total radio emission of NGC 4449 at 610 MHz, superimposed onto Hα (Klein et al. 1996)

Total radio emission of NGC 4449 at 8 GHz, and orientation of the magnetic field; the coloured image is Hα (Chyzy et al. 2000)
Dwarf galaxies NGC1569 and NGC4449: Why Choose These Two Targets?

- Sufficiently nearby:
  - NGC1569 → 3.36 ± 0.20 Mpc (Grocholski et al. 2008)
  - NGC4449 → 3.7 Mpc

- NGC1569 is a post-starburst dwarf, with a complex star formation history. The youngest starburst is likely to have ceased ~ 5 Myr ago (Grocholski et al. 2008, Angeretti et al. 2005, Greggio et al. 1998, Israel & de Bruyn 1988). NGC4449 has a strong ongoing starburst.

- Bright in the radio continuum, hence, observations possible, with good sensitivity and resolution.
The transport of a relativistic plasma out of this post-starburst galaxy was suggested by two observations (Mühle 2003):

- NGC1569 has a radio halo, extending out to about 2 kpc at 20 cm
- The projected orientation of its magnetic field is radial throughout
Radio images of NGC1569. Left: Continuum maps at four wavelengths (VLA, WSRT). At 20 cm, the first contour is at 50 μJy/b.a. Right: Magnetic field structure obtained at 3.6 cm (VLA), along with the rotation measure (colour wedge in units of $10^3$ rad m$^{-2}$), superimposed onto an Hα image (from Kepley et al. 2010).
Goals in Brief

- Bridging the gap between the higher frequencies and future observations with LOFAR:
  - Size of the synchrotron halos → find the relativistic particles
  - Spectral index as a function of galacto-centric distance → ages of the relativistic particles.
  - Perform a rotation-measure analysis → magnetic field structure around the dwarf galaxy → RM Synthesis
Observations with the Westerbork Synthesis Radio Telescope

<table>
<thead>
<tr>
<th>NGC 1569</th>
<th>NGC 4449</th>
</tr>
</thead>
<tbody>
<tr>
<td>13 Nov 2010</td>
<td>15 May 2011</td>
</tr>
<tr>
<td>92 cm, 350 MHz</td>
<td>92 cm, 350 MHz</td>
</tr>
<tr>
<td>12 hour run, maxi-short config</td>
<td>12 hour run, maxi-short config</td>
</tr>
<tr>
<td>128 channels, 4 polarisations, 8 bands, 10Mhz bandwith</td>
<td>128 channels, 4 polarisations, 8 bands, 10Mhz bandwith</td>
</tr>
<tr>
<td>Calibrators: 3C48, 3C286 (both unpolarised at this frequency!). Obtained polarized calibrator DA240 from an observation 5 days later.</td>
<td>Calibrators: 3C147, DA240</td>
</tr>
</tbody>
</table>
Results: Total Intensity

- RMS in the image is ~ 0.3 mJy/beam.
- The first contour is at 1 mJy/beam
- “boxy” structure, which is reminiscent of the morphology seen in X-rays and Hα.
- The extent of the radio halo is **7.8 kpc**, at 20 cm it was 4.4 kpc

Radio Continuum image of NGC1569 at 92 cm (WSRT).
Integrated radio continuum spectrum of NGC1569. Shown are the total flux densities (red squares), the free-free radiation (green crosses), and the synchrotron fluxes (blue stars), the latter obtained by subtracting the thermal from the total fluxes.

We assumed the free-free spectrum to have a slope $\alpha_{\text{th}} = -0.1$. The resulting free-free flux density is close to previous estimates (Israel & de Bruyn 1988, Lisenfeld et al. 2004).

The fitted non-thermal spectrum exhibits a cut-off frequency $\nu_b = 11$ GHz:

\[
S_v = S_{\text{nth}} \left( \frac{\nu}{\nu_b} \right)^{\alpha_{\text{nth}}} \cdot e^{-\frac{\nu}{\nu_b}}
\]

The exponential drop in the synchrotron spectrum is consistent with a single-burst injection spectrum and pitch-angle isotropisation (Kardashev 1962).
Radial Scale Length

![Graph showing the relationship between non-thermal intensity and radius. The data is labeled as 'Data NGC1569 @ 90cm', with a fitted curve and scale length indicated.]
- Spectral indices vary between 0.41 at the core upto 0.85 near the edges.
- Such flat spectra at the core are observed in a dwarf galaxy for the first time!
- Non-linear diffusive shock acceleration?!

Spectral index map of NGC 1569 using maps at 350 MHz, 1.4 GHz, 2.3 GHz, 4.9 GHz and 8.5 GHz
Radial Evolution of the Break Frequency

NGC 1569 Radial Break frequency

- $r = 120$ arcsec, $\nu_b = 46.5 \pm 39.3$ GHz
- $r = 160$ arcsec, $\nu_b = 13.7 \pm 10.0$ GHz
- $r = 200$ arcsec, $\nu_b = 7.9 \pm 7.6$ GHz
- $r = 240$ arcsec, $\nu_b = 4.4 \pm 3.6$ GHz
- $r = 280$ arcsec, $\nu_b = 2.8 \pm 4.8$ GHz
• Magnetic field strengths are calculated using the revised equipartition formula given by Beck & Krause, 2005.

• A spherical geometry of the synchrotron emitting medium has been assumed.

• Non-thermal intensities at 350 MHz were used.

• The total magnetic field strength at the core is $\approx 16 \, \mu G$ and falls off to $4 \, \mu G$ in the halo.
Spectral Ageing

Spectral age,

\[ t_{1/2} = 1.59 \cdot 10^9 \cdot \frac{B^{1/2}}{B^2 + B_{eq}^2} \cdot \left[ \left( \frac{\nu}{\text{GHz}} \right) \cdot (1 + z) \right]^{-1/2} \text{ yr}, \]

where \( B_{eq}^2 \) is replaced by the energy density of the radiation field, \( U_{rad} \), which can be estimated from the bolometric luminosity of the galaxy (Lisenfeld et al, 2004).

Also, from the linear fit shown in the figure, the wind velocity turns out to be \( \approx 570 \text{ km/s} \).
Total radio emission of NGC4449 at 350 MHz. RMS in the image is \(~0.5\) mJy/beam. First contour is at 1.5 mJy/beam.

Total radio emission of NGC4449 at 610 MHz, superimposed onto Hα (Klein et al. 1996)
Integrated Radio Continuum Spectrum

NGC 4449 Radio Continuum Spectrum

\[ S_{\text{th}, \ 1 \text{ GHz}} = 92 \pm 36 \text{ mJy} \]
\[ S_{\text{nth}, \ 1 \text{ GHz}} = 254 \pm 18 \text{ mJy} \]
\[ \nu_b = 7 \pm 6 \text{ GHz} \]
\[ \alpha_{\text{nth}} = -0.5 \text{ (fixed)} \]
**Conclusions**

- Extent of the synchrotron halo is larger at 350 MHz for NGC1569 as expected.
- Spectral indices at the core are as flat as 0.4 → **non-linear diffusive shock acceleration** of CREs.
- Break in the radio spectrum radially migrates towards lower frequencies → **electron cooling**.
- Equipartition magnetic field strength is a few μG.
- Estimated **wind velocity** is 570 km/s → **High!** Roughly a kpc in a Myr. Magnetization seems reasonable.
Future: LOFAR Observations

- Since LOFAR has become almost fully operational and begins to deliver data with high sensitivity and high dynamic range, it can be used to trace potentially existing low-frequency synchrotron halos around dwarf galaxies.

- The MKSP proposal for observations in the Tier-1 and Tier-2 LOFAR Surveys contains a sample of dwarf galaxies (including NGC 1569) in different stages of their starbursts.

- If the wind velocity in NGC 1569 is really as high as our results show, cosmic rays should be propagated further out, and larger synchrotron halos should be detected at LOFAR frequencies!

Thank you for listening!