Magnetising the universe with dwarf galaxies

A new low-frequency radio continuum perspective

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With LOFAR Magnetism KSP

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Magnetising the universe with dwarf galaxies

- Astrophysical magnetic fields have been observed on a wide variety of scales.
- From pulsars to galaxy clusters.
- $\sim$ nG field lines are expected to pervade cosmic filaments.
- Where did they come from?
    - Top-down:
        - Entire universe was magnetized by a global process.
        - Usually requires physics beyond the Standard Model.
    - Bottom-up:
        - Magnetization happens first on the small scales
        - Propagates to large scales through outflows, diffusion ...
        - Kronberg et al (1999): magnetized outflows from galaxies in the early universe.

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Magnetising the universe with dwarf galaxies

- Magnetised outflows from dwarf galaxies can permeate IGM with seed fields.
  - Kronberg et al (1999); Bertone et al (2006)
- We cannot observe dwarf galaxies at high-z
- ... but we can study their local universe counterparts.

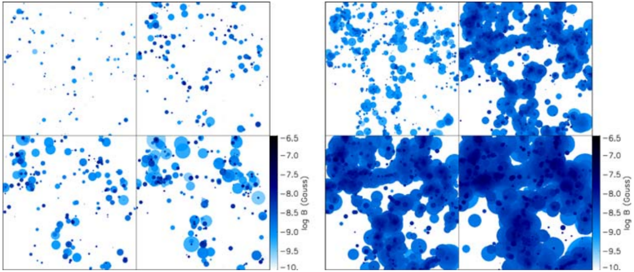


Image: Bertone et al (2006) for two different magnetic energy density (z=3, 1, 0.5, 0).

Dwarf galaxies sample

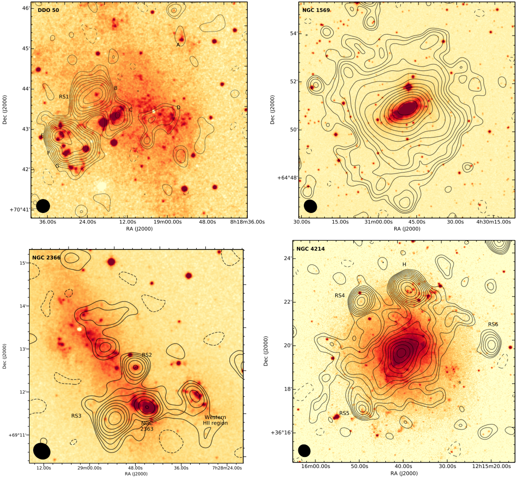
- Pilot study to observe 4 dwarf galaxies with LOFAR HBA (Observed in cycles 6/7).
- Same observational setup as the LOFAR Tier-1 Survey (LoTSS)
- Model cosmic ray transport in the radio halos.
- Four of the brightest galaxies from LITTLE-THINGS (Hunter et al. 2012)

Galaxies	Distance (D) [Mpc]	$\log_{10} \Sigma_{\mathrm{SFR}}$ [$M_\odot$ yr^{-1} kpc^{-2}]	M_{HI} [10^8 $M_\odot$]
NGC 1569	3.36	-0.01 ± 0.01	0.78
DDO 50	3.40	-1.55 ± 0.01	5.95
NGC 2366	3.44	-1.66 ± 0.01	6.49
NGC 4214	2.90	-1.08 ± 0.01	4.08

Distances: Grocholski et al. (2008), Dalcanton et al. (2009), and Tolstoy et al. (1995).
SFR – Hunter et al. (2010); H I mass – Walter et al. (2008);

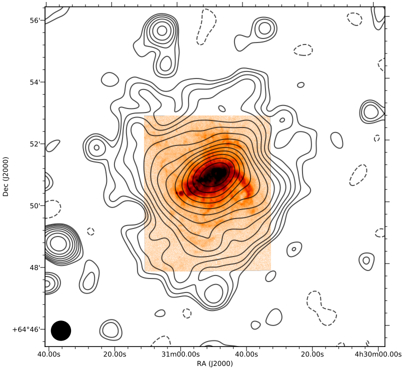
Dwarf galaxies: total intensity maps

- Diffuse emission seen around two of four dwarf galaxies.
- NGC 1569 is more extended (by a kpc) than at high frequencies (Kepley et al. 2010).
- NGC 1569 has a boxy morphology.
- Boxy morphology is seen in other spirals like NGC 5775.
- Unclear why some galaxies are boxy while most others are not.



NGC 1569

- A number of supershells are seen in NGC 1569
- Outflows larger than escape velocity detected in NGC 1569 (Martin et al 1995)



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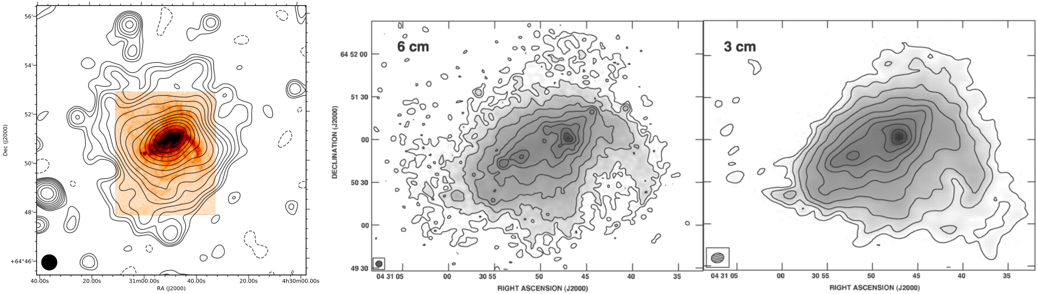
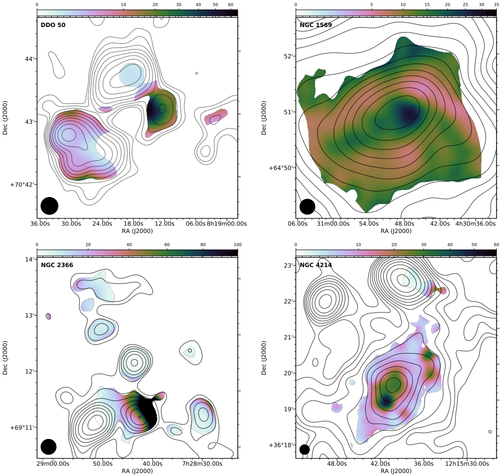


6 cm and 3 cm images: Kepley et al (2010)

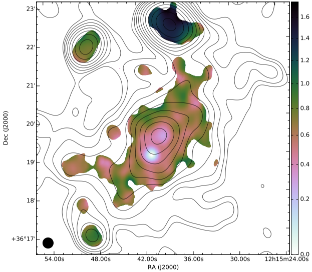
Dwarf galaxies: thermal fraction

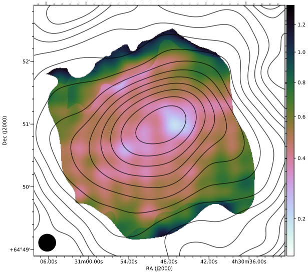
- Thermal subtraction using Hα and *Spitzer* 24 μm
  - See Kennicutt et al (2009) and Hunt et al (2004)
- $>$ 30% thermal fraction in several H II regions

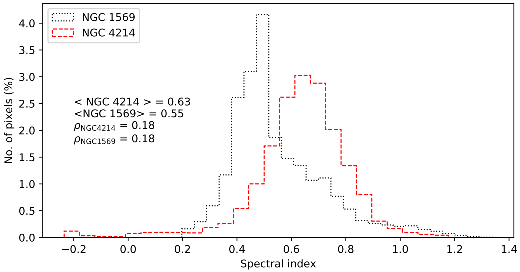


Dwarf galaxies: Non-thermal spectral index

- Spectral index between 150 MHz and 1.4 GHz
- H II regions show flat spectral index.
- Radial increase in non-thermal spectral index.

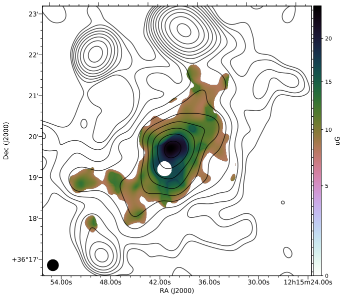


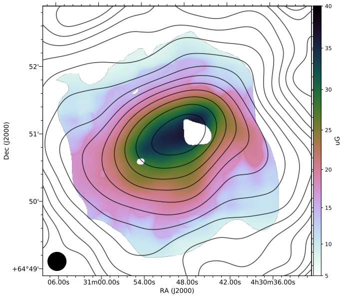




Dwarf galaxies: Magnetic field strengths

- Mean field strength in NGC 4214: 11.5 μ G.
- In NGC 1569, $B_{eq} \sim 32~\mu$ G in the optical disk and drops to $\sim 5~\mu$ G in the halo.
- Estimate field strengths are higher than what is seen in normal spiral galaxies.





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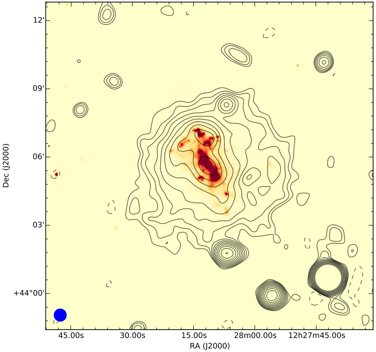
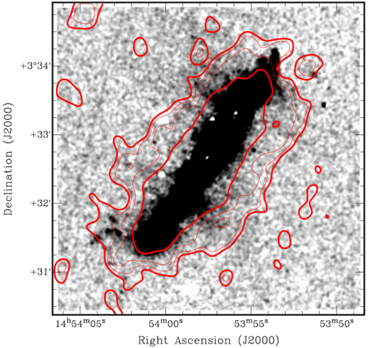
Radio halo around other galaxies

- Radio halos have been detected around other nearby dwarf and spiral galaxies.
- For example: NGC 4449 and NGC 5775

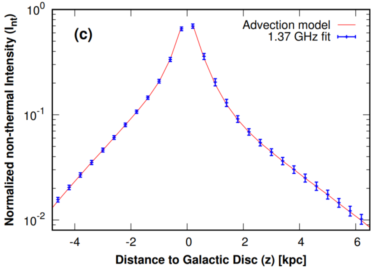




Images: Chyzy, Sridhar et al (in prep); Heald et al (in prep)

Modelling CR transport with pure advection/diffusion – Preliminary

- Heesen et al (2016) → 1D cosmic ray propagation model with advection/diffusion
- CR electrons are injected close to the mid-plane.
  - **See next talk by Volker Heesen for details.**
  - Synchrotron and inverse Compton losses.
  - Predicts a synchrotron emission spectra for
    - ⋆ a given magnetic field distribution, and
    - ⋆ a wind model.



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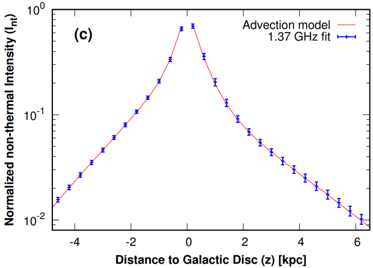
  - Predicts a synchrotron emission spectra for
    - a given magnetic field distribution, and
    - a wind model.
  - Close to 20 galaxies have been modelled this way
    - Mostly dominated by advection with few exceptions.
    - Advection speed ranges from 100 to 700 km s^{-1}
    - Advection speed appears to be correlate with SFR.



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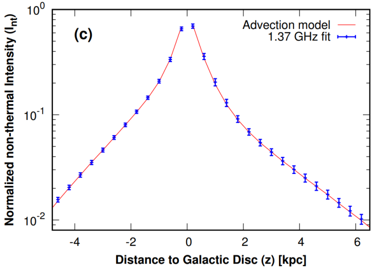

- In NGC 1569, advection dominated model fits well with speed $\sim$ 200 km/s.
  - Escape velocity at 2.2 kpc is $\sim$ 70 km/s. Johnson et al (2012)

Dwarf galaxies sample

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- Same observational setup as the LOFAR Tier-1 Survey (LoTSS)
- **Targetted observations deeper than LoTSS needed to build a larger sample.**
- Four of the brightest galaxies from LITTLE-THINGS (Hunter et al. 2012)

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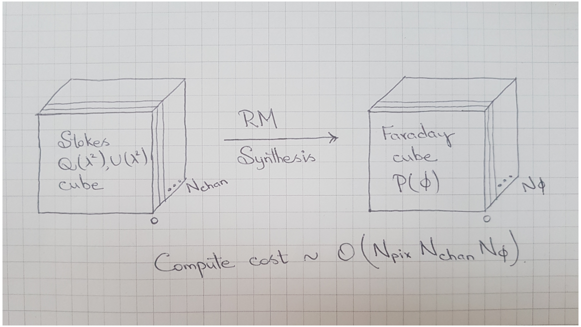
Rotation Measure synthesis

- Integrated part of wideband radio polarimetry pipelines.
- Wide bandwidth → large N_{chan} and N_{ϕ}
- Large field of view → large N_{pix}



RM synthesis – Computation cost

$$\widetilde{Q}(\phi_j) = K \sum_{i=1}^{N} Q_{\lambda i} \cos 2\phi_j(\lambda_i^2 - \lambda_0^2) + U_{\lambda i} \sin 2\phi_j(\lambda_i^2 - \lambda_0^2);\ \forall \phi_j \in [\phi_{\min}, \phi_{\max}] \tag{1}$$

$$\widetilde{U}(\phi_j) = K \sum_{i=1}^{N} U_{\lambda i} \cos 2\phi_j(\lambda_i^2 - \lambda_0^2) - Q_{\lambda i} \sin 2\phi_j(\lambda_i^2 - \lambda_0^2);\ \forall \phi_j \in [\phi_{\min}, \phi_{\max}]. \tag{2}$$

RM synthesis – Computation cost

$$\widetilde{Q}(\phi_j) = K \sum_{i=1}^{N} Q_{\lambda i} \cos 2\phi_j(\lambda_i^2 - \lambda_0^2) + U_{\lambda i} \sin 2\phi_j(\lambda_i^2 - \lambda_0^2);\ \forall \phi_j \in [\phi_{\rm min}, \phi_{\rm max}] \qquad (1)$$

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- **Compute cost** $\sim 15 \cdot \mathrm{N}_\phi \cdot \mathrm{N}_{\rm chan} \cdot \mathrm{N}_{\rm los}$
- For a typical 1.4 GHz Westerbork experiment, compute cost $\sim$ 1.3 TFLOPs
- For a typical LOFAR pointing, it is $\sim$ 1.5 PFLOPs!
- Easy to implement on Single Instruction/Multiple Data (SIMD) architecture

cuFFS: A GPU-accelerated RM synthesis package

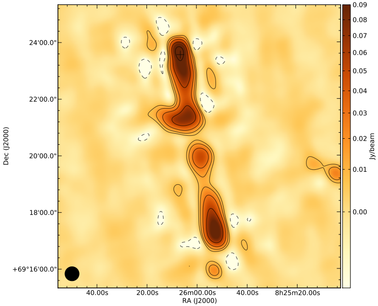
- Written in CUDA C. Supports both FITS and HDF5 file formats.
- **Upto 2 orders of magnitude faster** than other public codes.
- See https://github.com/sarrvesh/cuFFS or **ascl:1810:015**

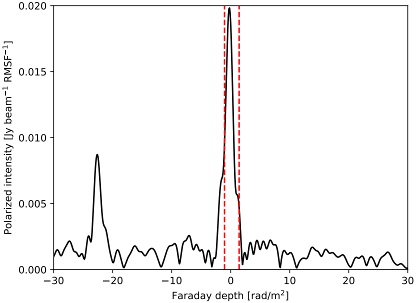
- Used to process the MWA polarization survey
  - POlarization from the GLEAM Survey (POGS). See Riseley et al (2018).
  - Cube size: $13000 \times 5000 \times 4000$

- Actively being developed:
  - Implement RM Clean
  - Faraday synthesis
  - Comments/feature requests welcome

Polarized emission – Background radio sources

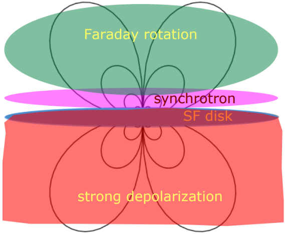
- 8C 0821+695 – Giant Radio Galaxy at $z = 0.53$
- Linear size: $7'.7 = 2.65$ Mpc
- '+' sign indicates the location of polarized emission

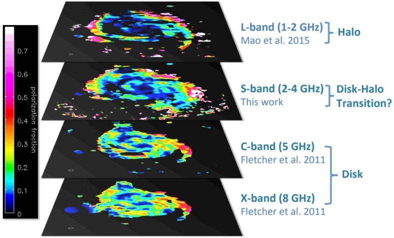




Polarized emission – Target galaxies

- None of the nearby galaxies studied so far have polarized emission at 150 MHz.
- Polarized emission at 150 MHz arises at large z
  - Ordered $\boldsymbol{B}$ is small at large z
  - Number density of relativistic electrons is small





Images: George Heald; Maja Kierdorf.

Summary

- We have detected radio halo around the nearby dwarf galaxy NGC 1569
- Cosmic ray transport model reveals magnetized outflows
  - advection velocity, $v_{\rm adv} \sim 200$ km/s
  - advection velocity larger than escape vlocity $v_{\rm esc} \sim 70$ km/s
- Observations deeper than LoTSS needed to build a larger sample.
- Detecting polarized emission from nearby galaxies is still challenging.