Interaction of galaxies with environment – magnetic draping

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in collaboration with

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Outline

1. Magnetic draping
   - Mechanism
   - Observations
   - Physical insight

2. Spiral galaxies
   - Polarized radio ridges
   - Magnetic draping simulations
   - Draping and synchrotron emission

3. Conclusions
What is magnetic draping?
**What is magnetic draping?**

- Is magnetic draping (MD) similar to ram pressure compression?
  - no density enhancement for MD
  - analytical solution of MD for incompressible flow
  - ideal MHD simulations *(right)*

- Is magnetic flux still frozen into the plasma?
  - yes, but plasma can also move along field lines while field lines get stuck at obstacle
Venus and Mars do not have a global magnetic field

**Venus Express**: amplification of solar wind field by a factor $\sim 6$ at the side facing the Sun

draping of solar wind magnetic field around Venus/Mars leads to the formation of magnetic pile-up region and the magneto tail → enhanced magnetic field strength in the planets’ wake
Streamlines in the rest frame of the galaxy

- Stokes function \( p(s, \theta) = \sqrt{3sR} \sin \theta \)
  \( \to \) critical impact parameter for \( \theta = \pi/2, s = l_{\text{drape}}: p_{\text{cr}} = R/(2\mathcal{M}_A) \)

- only those streamlines initially in a narrow tube of radius \( p_{\text{cr}} \approx R/20 \approx 1 \text{ kpc} \) from the stagnation line become part of the magnetic draping layer (color coded)
  \( \to \) constraints on \( \lambda_B \)

- the streamlines that do not intersect the tube get deflected away from the galaxy, become never part of the drape and eventually get accelerated (Bernoulli effect)

- note the kink feature in some draping-layer field lines due to back reaction as the solution changes from the hydrodynamic potential flow solution to that in the draped layer
Conditions for magnetic draping

- ambient plasma sufficiently ionized such that flux freezing condition applies
- super-Alfvénic motion of a cloud through a weakly magnetized plasma: \( \mathcal{M}_A^2 = \beta \gamma \mathcal{M}^2 / 2 > 1 \)
- magnetic coherence across the “cylinder of influence”:

\[
\frac{\lambda_B}{R} \gtrsim \frac{1}{\mathcal{M}_A} \sim 0.1 \times \left( \frac{\beta}{100} \right)^{-1/2}
\]

for sonic motions,

Here \( R \) denotes the curvature radius of the working surface at the stagnation line.
Polarized synchrotron emission in a field spiral: M51

- grand design ‘whirlpool galaxy’ (M51): optical star light superposed on radio contours
- polarized radio intensity follows the spiral pattern and is strongest in between the spiral arms
- the polarization ‘B-vectors’ are aligned with the spiral structure
3D simulations show that the ram-pressure wind quickly strips the low-density gas in between spiral arms (Tonnesen & Bryan 2010).

being flux-frozen into this dilute plasma, the large scale magnetic field will also be stripped

→ resulting radio emission should be unpolarized

Brueggen (2008)
Polarized synchrotron ridges in Virgo spirals

Vollmer et al. (2007): 6 cm PI (contours) + B-vectors; Chung et al. (2009): HI (red)
Observational evidence and model challenges

- asymmetric distributions of polarized intensity at the leading edge with extraplanar emission, sometimes also at the side
- coherent alignment of polarization vectors over $\sim 30$ kpc
- stars lead polarized emission, polarized emission leads gas
- HI gas only moderately enhanced (factor $\lesssim 2$), localized ‘HI hot spot’ smaller than the polarized emission region:
  $$n_{\text{compr}} \approx n_{\text{icm}} v_{\text{gal}}^2 / c_{\text{ism}}^2 \approx 1 \text{ cm}^{-3} \approx \langle n_{\text{ism}} \rangle$$
- flat radio spectral index (similar to the Milky Way) that steepens towards the edges of the polarized ridge
- no or weak Kelvin-Helmholtz instabilities at interface detectable

$\rightarrow$ previous models that use ram-pressure compressed galactic magnetic fields fail to explain most of these points!
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→ Need to consider the full MHD of the interaction spiral galaxy and magnetized ICM!
Magnetic draping around a spiral galaxy

Athena simulations of spiral galaxies interacting with a uniform cluster magnetic field. There is a sheath of strong field draped around the leading edge (shown in red).

Magnetic draping around a spiral galaxy – physics

- The galactic ISM is pushed back by the ram pressure wind $\rho v^2$.
- The stars are largely unaffected and lead the gas.
- The draping sheath is formed at the contact of galaxy/cluster wind.
- As stars become SN, their remnants accelerate CRes that populate the field lines in the draping layer.

- CRes are transported diffusively (along field lines) and advectively as field lines slip over the galaxy.
- CRes emit radio synchrotron radiation in the draped region, tracing out the field lines there → coherent polarized emission at the galaxies’ leading edges.

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Modeling the electron population

- typical SN rates imply a homogeneous CRe distribution (WMAP)
- FIR-radio correlation of Virgo spirals show comparable values to the solar circle → take CRe distribution of our Galaxy:

\[ n_{\text{cre}} = C_0 \, e^{-\frac{(R-R_{\odot})}{h_R}} \, e^{-|z|/h_z} \]

with normalization \( C_0 \simeq 10^{-4} \, \text{cm}^{-3} \),
scale heights \( h_R \simeq 8 \, \text{kpc} \) and \( h_z \simeq 1 \, \text{kpc} \) at Solar position

- truncate at contact of ISM-ICM, attach exp. CRe distribution \( \perp \) to contact surface with \( h_\perp \simeq 150 \, \text{pc} \) (max. radius of Sedov phase)
Magnetic draping and polarized synchrotron emission

Synchrotron B-vectors reflect the upstream orientation of cluster magnetic fields
Simulated polarized synchrotron emission

Movie of the simulated polarized synchrotron radiation viewed from various angles and with two field orientations.
Magnetic draping of a helical B-field
(Non-)observation of polarization twist constrains magnetic coherence length
Magnetic coherence scale estimate by radio ridges

- Observed polarised draping emission → field coherence length $\lambda_B$ is at least galaxy-sized
- If $\lambda_B \sim 2R_{\text{gal}}$, then the change of orientation of field vectors imprint as a change of the polarisation vectors along the vertical direction of the ridge showing a ‘polarisation-twist’

- The reduced speed of the boundary flow means that a small $L_{\text{drape}}$ corresponds to a larger length scale of the unperturbed magnetic field ahead of the galaxy NGC 4501

$$L_{\text{coh}} \approx \eta L_{\text{drape}} v_{\text{gal}} / v_{\text{drape}} = \eta \tau_{\text{syn}} v_{\text{gal}} > 100 \text{ kpc},$$

with $\tau_{\text{syn}} \sim 5 \times 10^7 \text{ yr}$, $v_{\text{gal}} \sim 1000 \text{ km/s}$, and a geometric factor $\eta \sim 2$
Varying galaxy inclination and magnetic tilt

Side view:
Galaxy moving upwards

Inclination of
galaxy toward
direction of motion

Top view:
Galaxy moving out of page

Tilt of
magnetic field
orientation
Observations versus simulations

A. Ram-pressure stripped tail

B. HI hot spot

C. Projected normal to the PI hot spot

D. Projected proper motion vector

E. Ram-pressure stripped tail

F. HI hot spot

Magnetic draping simulations

Draping and synchrotron emission

Spiral galaxies

Conclusions
Biases in inferring the field orientation

- **Uncertainties in estimating the 3D velocity:** $v_r$, ram-pressure stripped gas visible in HI morphology $\rightarrow \hat{v}_t$

- **Direction-of-motion asymmetry:** magnetic field components in the direction of motion bias the location of $B_{\text{max, drape}}$ (figure to the right):
  - Draping is absent if $B \parallel v_{\text{gal}}$

- **Geometric bias:** polarized synchrotron emission only sensitive to traverse magnetic field $B_t$ (⊥ to LOS) $\rightarrow$ maximum polarised intensity may bias the location of $B_{\text{max, drape}}$ towards the location in the drape with large $B_t$
Mapping out the magnetic field in Virgo

NGC 4501

NGC 4654

υ < 600 km/s
600 km/s < υ < 1300 km/s
1300 km/s < υ < 2000 km/s
2000 km/s < υ

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Magnetic draping
The alignment of the field in the plane of the sky is significantly more radial than expected from random chance. Considering the sum of deviations from radial alignment gives a chance coincidence of less than 1.7% ($\sim 2.2 \sigma$).

For the three nearby galaxy pairs in the data set, all have very similar field orientations.

Which effect causes this field geometry?

- Radial infall? (Ruszkowski+2010)
Magnetic draping with LOFAR

- **NGC 4501**: 5 GHz polarized intensity
- lower frequency
  → longer electron cooling time
  → larger magnetic drape!
- length scale of draping sheath:

\[
\gamma = \left( \frac{2\pi \nu_{\text{syn}} m_e c}{3 e B} \right)^{1/2} \approx 10^4 \left( \frac{\nu_{\text{syn}}}{5 \text{ GHz}} \right)^{1/2} \left( \frac{B}{7 \mu \text{G}} \right)^{-1/2},
\]

\[
\tau_{\text{syn}} = \frac{6\pi m_e c}{\sigma_T B^2 \gamma} \approx 50 \text{ Myr} \left( \frac{\nu_{\text{syn}}}{5 \text{ GHz}} \right)^{-1/2} \left( \frac{B}{7 \mu \text{G}} \right)^{-3/2},
\]

\[
L_{\text{drape}} = \eta v_{\text{drape}} \tau_{\text{syn}} \approx 10 \text{ kpc} \left( \frac{\nu_{\text{syn}}}{5 \text{ GHz}} \right)^{-1/2} \approx 60 \text{ kpc} \left( \frac{\nu_{\text{syn}}}{150 \text{ MHz}} \right)^{-1/2},
\]

with velocity in draping layer \( v_{\text{drape}} \approx 100 \text{ km s}^{-1} \) and a geometric factor \( \eta \approx 2 \).
Conclusions on magnetic draping around galaxies

- Draping of cluster magnetic fields naturally explains polarization ridges at Virgo spirals.

This represents a new tool for measuring the in situ 3D orientation and coherence scale of cluster magnetic fields. Application to the Virgo cluster shows that the magnetic field is preferentially aligned radially. This finding implies efficient thermal conduction across clusters, leading to thermal cluster history and cluster cosmology. Great prospects for LOFAR observations include uncovering the history of the magnetic drape.
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Great prospects for LOFAR observations: uncovering the history of the magnetic drape.

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- this finding implies efficient thermal conduction across clusters → thermal cluster history & cluster cosmology
- great prospects for LOFAR observations: uncovering the history of the magnetic drape
Literature for the talk

- Pfrommer & Dursi, 2010, Nature Phys., 6, 5206, *Detecting the orientation of magnetic fields in galaxy clusters*

Magneto-thermal instability: the idea

Convective stability in a gravitational field:

- Classical Schwarzschild criterion: $\frac{dS}{dz} > 0$
- Long MFP, Balbus criterion: $\frac{dT}{dz} > 0$
- New instability causes field lines to reorient radially → efficient thermal conduction radially (close to Spitzer)

The non-linear behavior of the MTI (Parrish & Stone 2007).

- Adiabatic boundary conditions for $T(r)$: the instability can exhaust the source of free energy → isothermal profile
- Fixed boundary conditions for $T(r)$: field lines stay preferentially radially aligned (35 deg mean deviation from radial)
Gravitational shock wave heating

Observed temperature profile in clusters is decreasing outwards → heat also flows outwards along the radial magnetic field. 

*How is the temperature profile maintained? → gravitational heating*

shock strengths weighted by dissipated energy

energy flux through shock surface

\[ \frac{\dot{E}_{\text{diss}}}{R^2} \sim \rho \nu^3 \]

→ increase towards the center