Cosmological shocks and magnetic fields in galaxy clusters

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in collaboration with

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Outline

1. Probing accretion shocks
   - Introduction
   - A puzzling radio galaxy
   - Perseus accretion shock

2. Magnetic draping
   - Introduction
   - MHD Simulations
   - Astrophysical insight

3. Spiral galaxies
   - Polarized radio ridges
   - Galaxy draping
   - Implications
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Shocks and magnetic fields in galaxy clusters
A theorist’s perspective of a galaxy cluster . . .

Galaxy clusters are dynamically evolving dark matter potential wells:

- Energy
- Space

- Shock waves heat the infalling gas to the virial temperature
- Galaxy velocity dispersion probes the DM potential

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Shocks and magnetic fields in galaxy clusters
Probing accretion shocks
Magnetic draping
Spiral galaxies

Introduction
A puzzling radio galaxy
Perseus accretion shock

... and how the observer’s Universe looks like

1E 0657-56 ("Bullet cluster")
(X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.)

Abell 3667
(radio: Johnston-Hollitt. X-ray: ROSAT/PSPC.)
Wish list for shocks

What we would like to measure and hope to infer:

- jump conditions: shock strength
- upstream properties: infalling WHIM
- post- and pre-shock conditions: geometry, obliquity
- shock curvature: vorticity and $B$ field generation
- post-shock turbulence: power spectrum, non-thermal pressure support
- ...

X-rays give limited insight → new complementary tools!
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Total synchrotron intensity of NGC 1265

O’Dea & Owen (1986): 4.9 GHz (left) and 1.4 GHz (right)
Bipolar AGN jets in an ICM wind: magnetic field

credit: Porter, Mendygral & Jones

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Shocks and magnetic fields in galaxy clusters
Bipolar AGN jets in an ICM wind: synthetic radio

credit: Porter, Mendygral & Jones
Radio properties of NGC 1265

Sijbring & de Bruyn (1998), *left*: radio intensity $I_{600 \text{ MHz}}$; *right*: variations of $I_{600 \text{ MHz}}$ (*triangles*), $I_{150 \text{ MHz}}$ (*squares*) and spectral index (*bottom*) along the tail
Previous models of NGC 1265 and why they fail

1. Chance superposition of several independent head-tail galaxies
   → lack of observed strong radio sources in this field
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Shocks and magnetic fields in galaxy clusters
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3. ‘radio tail’ traces a helical cluster wind
   → wind needs special alignment with LOS, fine-tuned
   re-acceleration that balances electron cooling and avoids
   fanning out the well-confined radio emission along the arc
Previous models of NGC 1265 and why they fail

1. Chance superposition of several independent head-tail galaxies → *lack of observed strong radio sources in this field*

2. Re-acceleration of electrons in the turbulent wake of a galaxy → *contrived projection probabilities and implausible energetics (re-acceleration efficiency \( \sim 3\% \))*

3. ‘Radio tail’ traces a helical cluster wind → *wind needs special alignment with LOS, fine-tuned re-acceleration that balances electron cooling and avoids fanning out the well-confined radio emission along the arc*

4. ‘Radio tail’ outlines ballistic orbit of NGC 1265 → *requires dark object with \( M \gtrsim M_{\text{NGC 1265}} \approx 3 \times 10^{12} M_\odot \) orbiting the galaxy, no explanation of change of orbit and same challenges regarding electron cooling and re-acceleration*
Requirements for any model of NGC 1265

- bright narrow angle tail radio jet: synchrotron cooling
- transition region: change of winding direction and sharp drop in $S_\nu$ and $\alpha$
- coherent properties along the dim radio ring, confined morphology

→ we are looking at 2 electron populations in projection possibly suggesting 2 different epochs of feedback:

→ active jet + detached radio bubble that recently got energized coherently across 300 kpc → shock?
Shock overruns an aged radio bubble (C.P. & Jones 2011)
Probing accretion shocks
Magnetic draping
Spiral galaxies

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Bubble transformation to vortex ring

Enßlin & Brüggen (2002): gas density (top) and magnetic energy density (bottom)
Synthetic radio emission of shock-transformed bubble

Enßlin & Brüggen (2002): total 100 MHz intensity and polarization E-vectors, strong shock/weak $B$ (left) and strong shock/strong $B$ model (right)

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C.P. & Jones (2011):
NGC 1265 as a perfect probe of a shock

- **idea:**
  - galaxy velocity not affected by shock → **pre-shock conditions**
  - tail & torus as tracers of the **post-shock flow**

- **assumptions:**
  - shock surface \( \parallel \) gravitational equipotential surface of Perseus
  - recent jet launched shortly after shock crossing

- **method:**
  - extrapolating position and velocity back in time
  - employing conservation laws at oblique shock
  - iterate until convergence
Derived geometry for NGC 1265

C.P. & Jones (2011)
Shock strength and jump conditions

- shock compresses relativistic bubble adiabatically: \( \frac{P_2}{P_1} = C^{4/3} \)
- bubble compression factor:
  \[ C = \frac{V_{\text{bubble}}}{V_{\text{torus}}} = \frac{\frac{4}{3} \pi R^3}{2 \pi^2 R r_{\text{min}}^2} = \frac{2}{3 \pi} \left( \frac{R}{r_{\text{min}}} \right)^2 \approx 10 \]
- assuming pressure equilibrium → shock jumps:
  \[ \frac{P_2}{P_1} \approx 21.5, \quad \frac{\rho_2}{\rho_1} \approx 3.4, \quad \frac{T_2}{T_1} \approx 6.3, \quad \text{and} \quad M \approx 4.2 \]

C.P. & Jones (2011)
Perseus accretion shock and WHIM properties

- jet has low Faraday RM → NGC 1265 on near side of Perseus
  NGC 1265 redshifted w/r to Perseus → infalling system
  → shock likely the accretion shock

- extrapolating X-ray \( n \)- and \( T \)-profiles to \( R_{200} \) & shock jumps:
  → upper limits on infalling warm-hot intergalactic medium

\[
\begin{align*}
  kT_1 & \lesssim 0.4 \text{ keV} \\
  n_1 & \lesssim 5 \times 10^{-5} \text{ cm}^{-3} \\
  P_1 & \lesssim 3.6 \times 10^{-14} \text{ erg cm}^{-3}
\end{align*}
\]

C.P. & Jones (2011)
Shear flows and shock curvature

- ellipticity of radio torus (magnitude and orientation) & bending direction of tail → excludes projection effects → evidence for post-shock shear flow

- shock curvature injects vorticity that shears the gas westwards:

\[ \frac{\varepsilon_{\text{shear}}}{\varepsilon_{\text{th,2}}} = \frac{\mu m_p v_\perp^2}{3 kT_2} \simeq 0.14, \]

with \( kT_2 \simeq 2.4 \text{ keV} \) and \( v_\perp \simeq 400 \text{ km/s} \).

C.P. & Jones (2011)
Conclusions on radio galaxies as probes of shocks

- consistent 3D model of NGC 1265
- prediction of a very interesting source class for LOFAR
- radio galaxies as perfect probes of pre- and post-shock flows:
  - hydrodynamic jumps and Mach numbers
  - statistical properties of the infalling WHIM (+ X-rays)
  - estimating the curvature radius of shocks and induced shear flows

→ implications for intra-cluster turbulence as well as generation and amplification of large-scale magnetic fields!
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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
Applications of magnetic draping

- solar system: plasma physics
- hydrodynamic stability of radio bubbles (Dursi 2007, Ruszkowski+2007)
- sharpness ($T_e$, $n_e$) of cold fronts: without $B$, smoothed out by diffusion and heat conduction on $\gtrsim 10^8$ yrs (Lyutikov 2004, Dursi+2008)
- magnetic draping on spiral galaxies: method for detecting the orientation of cluster fields (C.P.+2010)

Guicking et al. (2010): magnetic draping around Venus
Sometimes, 2D just isn’t enough . . .
**MHD solution: kinematic approx. vs. AMR simulation**

$B_x, B_y, B_z$ in the plane of the initial B-field

**Introduction**

MHD Simulations

Astrophysical insight

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**Shocks and magnetic fields in galaxy clusters**
MHD solution: kinematic approx. vs. AMR simulation

$B_x, B_y, B_z$ in the plane perpendicular to the initial B-field

-4 -2 0 2 4
26
28
30
32
34
36
38

B y of kinematic MHD solution

-4 -2 0 2 4
26
28
30
32
34
36
38

B z of kinematic MHD solution

-0.4 -0.1 0.2 0.5 0.8

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Shocks and magnetic fields in galaxy clusters
Thickenss of the draping sheath – simulations

amplified draping field \( B = \frac{B_0}{\sqrt{1 - \frac{R^3}{r^3}}} \), \( l_{\text{drape}} \simeq \frac{R}{12M_A^2} \simeq (10 - 100) \text{ pc} \)

\textit{left:} fitting peak position and a fall-off radius of the theory prediction;  
\textit{right:} density cut-planes; circle shows radius and position given by the fit to the magnetic field structure, left;

\( \rightarrow \) astonishing agreement of curvature radius at the working surface with potential flow predictions!
Streamlines in the rest frame of the galaxy

- Stokes function \( p(s, \theta) = \sqrt{3sR} \sin \theta \)
  → 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 \( p_{\text{cr}} \approx R/20 \approx 1 \) kpc from the stagnation line become part of the magnetic draping layer (color coded)
  → 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
Streamlines in the rest frame of the galaxy

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

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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.
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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
Brueggen (2008)

- 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
Polarized synchrotron ridges in Virgo spirals

Vollmer et al. (2007): 6 cm PI (contours) + B-vectors; Chung et al. (2009): HI (red)
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 $\sim \rho v^2$
- 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 $\rightarrow$ coherent polarized emission at the galaxies’ leading edges
Modeling the electron population

- cooling time scale of synchrotron emitting electrons (CRe):

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

\[
\tau_{\text{sync}} = \frac{E}{\dot{E}} = \frac{6\pi m_e c}{\sigma_T B^2 \gamma} \approx 5 \times 10^7 \text{ yr} \left( \frac{\gamma}{10^4} \right)^{-1} \left( \frac{B}{7 \mu \text{G}} \right)^{-2}
\]

- typical SN rates imply a homogeneous CRe distribution (WMAP)

- FIR-radio correlation of Virgo spirals show comparable values to the solar circle: take MW CRe distribution inside our galaxies,

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

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

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

Synchrotron B-vectors reflect the upstream orientation of cluster magnetic fields

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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

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

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

Top view: Galaxy moving out of page
Observations versus simulations

- A: ram-pressure stripped tail
  - HI hot spot
  - PI hot spot
  - projected proper motion vector
  - projected normal to the PI hot spot

- B: HI hot spot
- C: Shocks and magnetic fields in galaxy clusters

- D: HI hot spot
  - PI hot spot
  - projected proper motion vector
  - ram-pressure stripped tail

- E: Total PI = 12.41 mJy
  - Max PI = 354.4 mJy/beam

- F: Total PI = 0.186 mJy
  - Max PI = 97.9 mJy/beam

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Biases in inferring the field orientation

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

- 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 $B \parallel \mathbf{v}_{\text{gal}}$

- Geometric bias: polarized synchrotron emission only sensitive to traverse magnetic field $B_t$ ($\perp$ 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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Shocks and magnetic fields in galaxy clusters
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)
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

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)
**Magneto-thermal instability: the idea**

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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

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

→ increase towards the center
Implications for galaxy clusters (probing cosmology)

- **How are galaxy clusters thermally stabilized?**
  → radial magnetic field in non-cool core clusters implies efficient thermal conduction that stabilizes these systems against entering a cooling catastrophe
  → thermal history + clusters as cosmological probes

- current cosmological cluster simulations fail to reproduce these clusters
  → magnetic fields + anisotropic conduction

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Cavagnolo et al. (2009)
Speculation: evolutionary sequence of galaxy clusters

- After a merging event of a non-cool core cluster, the injected turbulence decays on an eddy turnover time
  \[ \tau_{\text{eddy}} \approx \frac{L_{\text{eddy}}}{v_{\text{turb}}} \approx \frac{300 \text{ kpc}}{(300 \text{ km/s})} \approx 1 \text{ Gyr}. \]

- The magneto-thermal instability grows on a similar timescale of less than 1 Gyr and the magnetic field becomes radially oriented.

- The efficient thermal conduction stabilizes this cluster until a cooling instability in the center may cause the cluster to enter a cooling core state – similar to Virgo now – and requires possibly self-regularized heating by a super-massive black hole to be stabilized.
Conclusions on magnetic draping around galaxies

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

NGC 4501: draping of cluster magnetic fields naturally explains polarization ridges at Virgo spirals.
Conclusions on magnetic draping around galaxies

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- this represents a new tool for measuring the in situ 3D orientation and coherence scale of cluster magnetic fields
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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 that stabilizes these non-cool core systems.
- Important implications for thermal cluster history → galaxy cluster cosmology.
Probing accretion shocks
Magnetic draping
Spiral galaxies
Polarized radio ridges
Galaxy draping
Implications

Literature for the talk

  *Radio Galaxy NGC 1265 unveils the Accretion Shock onto the Perseus Galaxy Cluster*

• Pfrommer & Dursi, 2010, Nature Phys., 6, 520, 
  *Detecting the orientation of magnetic fields in galaxy clusters*

  *Draping of cluster magnetic fields over bullets and bubbles - morphology and dynamic effects*