Interaction of galaxies with environment – magnetic draping

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in collaboration with

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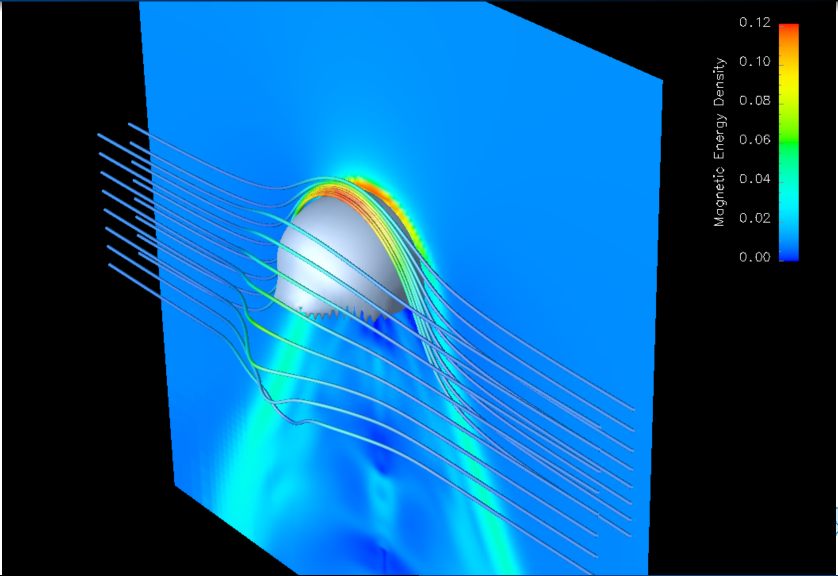
Nov 25, 2011 / LOFAR Magnetism KSP Workshop, Bologna

Outline

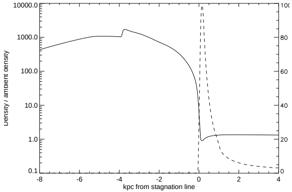
1. Magnetic draping
   - Mechanism
   - Observations
   - Physical insight
2. Spiral galaxies
   - Polarized radio ridges
   - Magnetic draping simulations
   - Draping and synchrotron emission
3. Conclusions

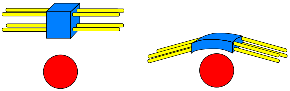
What is magnetic draping?



What is magnetic draping?

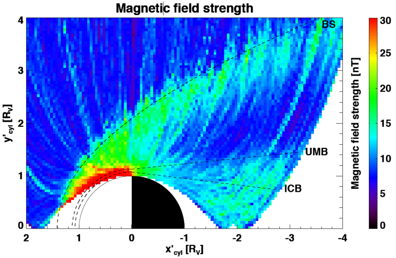
- Is magnetic draping (MD) similar to ram pressure compression?
  → no density enhancement for MD
  - analytical solution of MD for incompressible flow
  - ideal MHD simulations *(right)*
- Is magnetic flux still frozen into the plasma?
  yes, but plasma can also move along field lines while field lines get stuck at obstacle





Draping of the interplanetary field over Venus

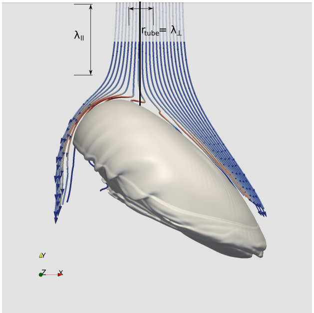
- Venus and Mars do not have a global magnetic field
- *Venus Express:* amplification of solar wind field by a factor ~ 6 at the side facing the Sun



Guicking et al. (2010)

- draping of solar wind magnetic field around Venus/Mars leads to the formation of magnetic pile-up region and the magneto tail $\rightarrow$ enhanced magnetic field strength in the planets' wake

Streamlines in the rest frame of the galaxy



- Stokes function $p(s,\theta) = \sqrt{3sR}\,\sin\theta$ $\rightarrow$ critical impact parameter for $\theta = \pi/2$, $s = l_{\rm drape}$: $p_{\rm cr} = R/(2\mathcal{M}_A)$
- only those streamlines initially in a narrow tube of radius $p_{\rm cr} \simeq R/20 \simeq 1$ kpc from the stagnation line become part of the magnetic draping layer (color coded) $\rightarrow$ constraints on λ_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

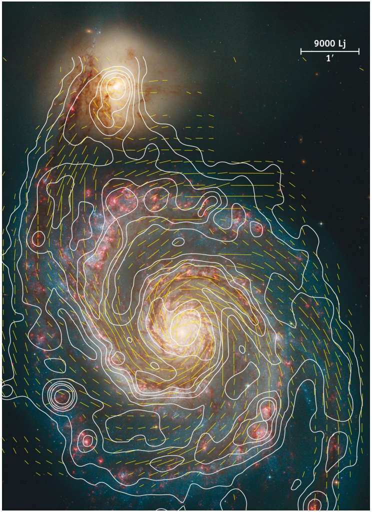
Conditions for magnetic draping

- 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":

$$\frac{\lambda_B}{R} \gtrsim \frac{1}{\mathcal{M}_A} \sim 0.1 \times \left(\frac{\beta}{100}\right)^{-1/2} \quad \text{for sonic motions,}$$

Here R denotes the curvature radius of the working surface at the stagnation line.

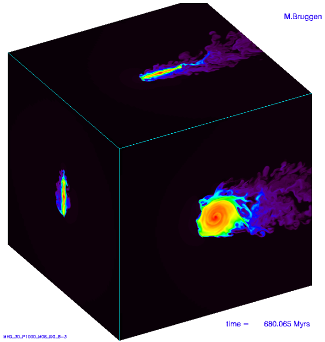
Polarized synchrotron emission in a field spiral: M51



MPIfR Bonn and Hubble Heritage Team

- 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

Ram-pressure stripping of cluster spirals

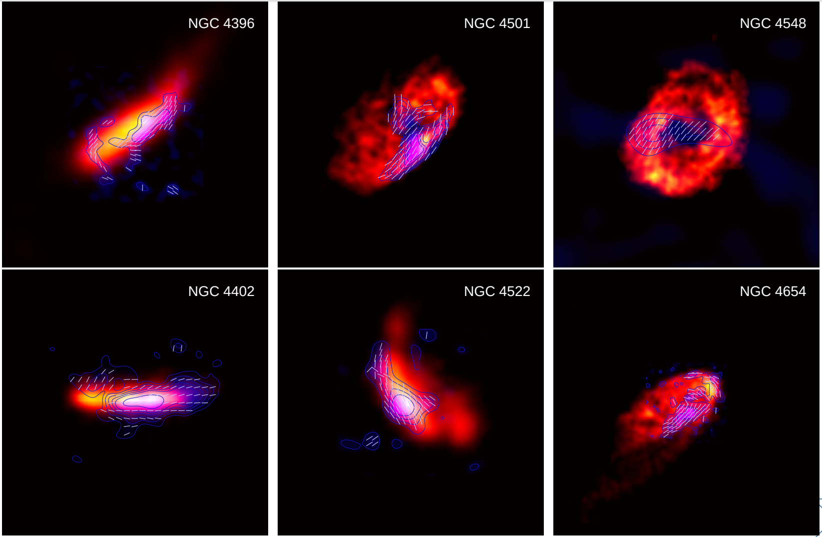


Brueggen (2008)

- 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)

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:
  $n_\mathrm{compr} \simeq n_\mathrm{icm}\, \upsilon_\mathrm{gal}^2 / c_\mathrm{ism}^2 \simeq 1\,\mathrm{cm}^{-3} \simeq \langle n_\mathrm{ism} \rangle$
- 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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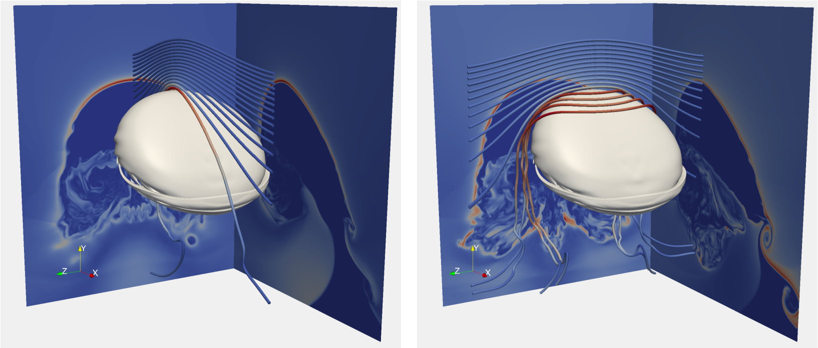
$\rightarrow$ need to consider the full MHD of the interaction spiral galaxy and magnetized ICM !

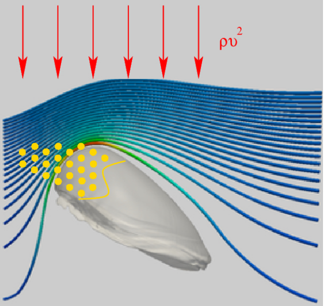
Magnetic draping around a spiral galaxy



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).

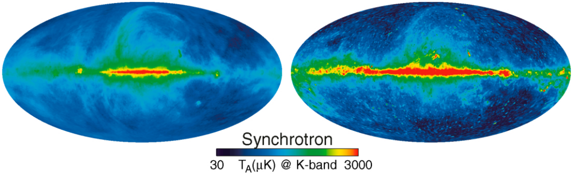
C.P. & Dursi, 2010, Nature Phys.

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



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

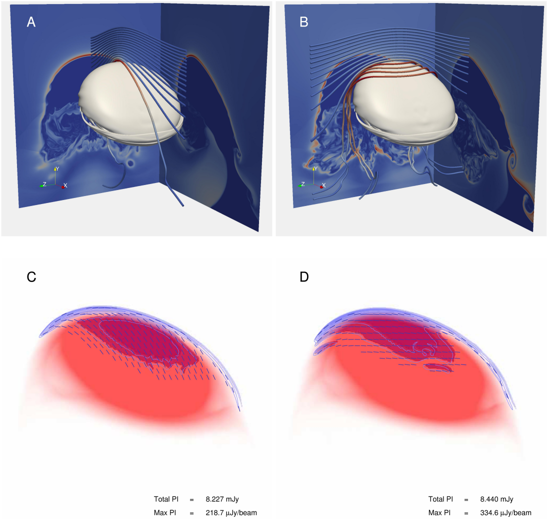
$$n_{\rm cre} = C_0 \, e^{-(R-R_\odot)/h_R} e^{-|z|/h_z}$$

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

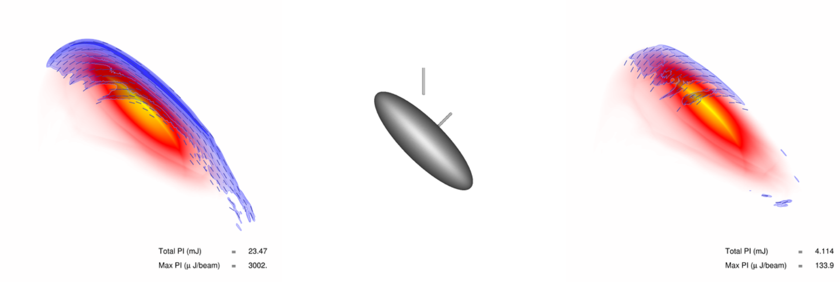
- truncate at contact of ISM-ICM, attach exp. CRe distribution $\perp$ to contact surface with $h_\perp \simeq 150\,\mathrm{pc}$ (max. radius of Sedov phase)

Magnetic draping and polarized synchrotron emission

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



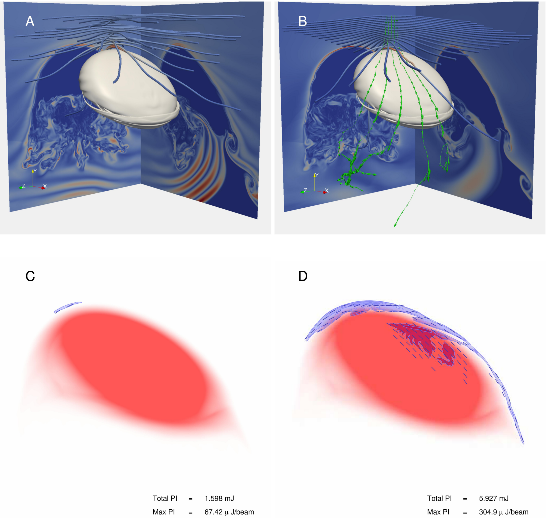
Simulated polarized synchrotron emission



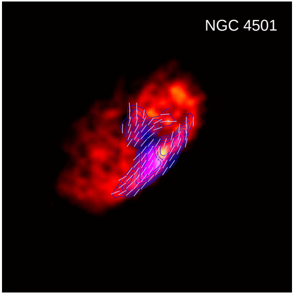
Movie of the simulated polarized synchrotron radiation viewed from various angles and with two field orientations.

Magnetic draping of a helical B-field

(Non-)observation of polarization twist constrains magnetic coherence length



Magnetic coherence scale estimate by radio ridges



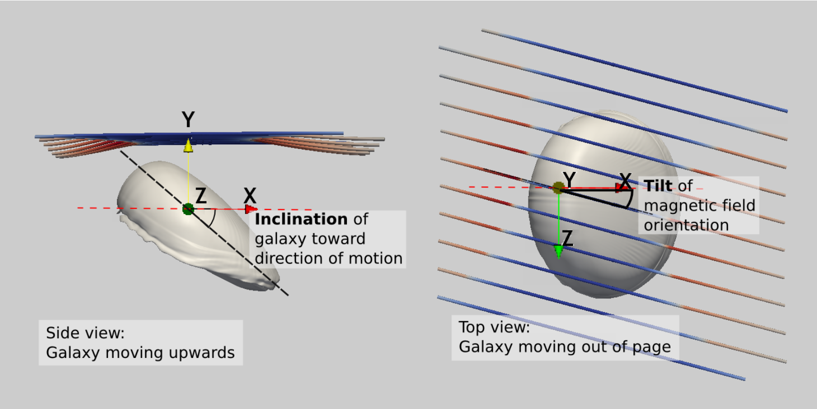
- observed polarised draping emission $\rightarrow$ field coherence length λ_B is at least galaxy-sized
- if $\lambda_B \sim 2R_{\rm gal}$, then the change of orientation of field vectors imprint as a change of the polarisation vectors along the vertical direction of the ridge showing a 'polarisation-twist'

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

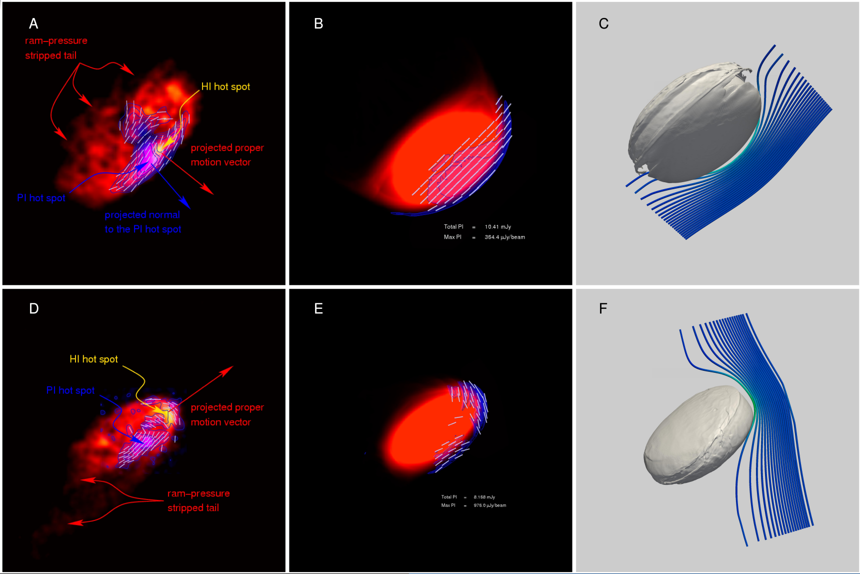
$$L_{\rm coh} \simeq \eta L_{\rm drape} v_{\rm gal}/v_{\rm drape} = \eta \tau_{\rm syn} v_{\rm gal} > 100\,{\rm kpc},$$

with $\tau_{\rm syn} \simeq 5 \times 10^7$ yr, $v_{\rm gal} \simeq 1000\,{\rm km/s}$, and a geometric factor $\eta \simeq 2$

Varying galaxy inclination and magnetic tilt

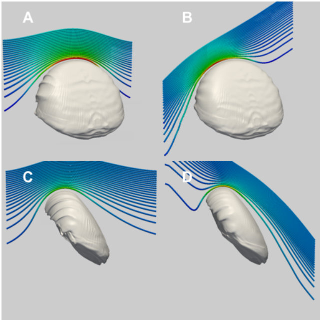


Observations versus simulations



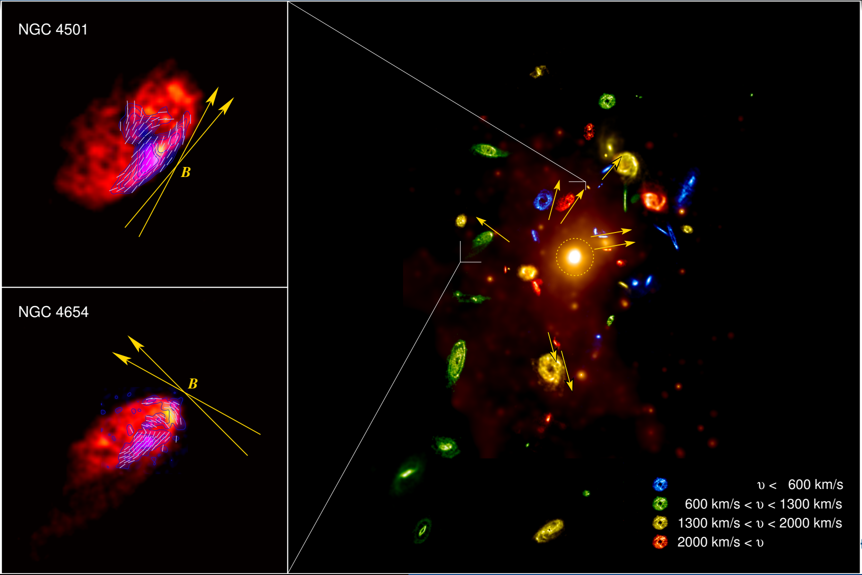
Biases in inferring the field orientation

- uncertainties in estimating the 3D velocity: v_r, ram-pressure stripped gas visible in HI morphology $\rightarrow \hat{\boldsymbol{v}}_{\mathrm{t}}$
- *direction-of-motion asymmetry:* magnetic field components in the direction of motion bias the location of $B_{\mathrm{max,\ drape}}$ (figure to the right): draping is absent if $\boldsymbol{B} \parallel \boldsymbol{v}_{\mathrm{gal}}$



- *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 $B_{\mathrm{max,\ drape}}$ towards the location in the drape with large B_{t}

Mapping out the magnetic field in Virgo



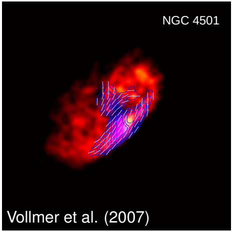
Discussion of radial field geometry

- 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.

$\rightarrow$ Which effect causes this field geometry?

Magneto-thermal instability? (Parrish+2007, C.P.+2010)
Radial infall? (Ruszkowski+2010)

Magnetic draping with LOFAR



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

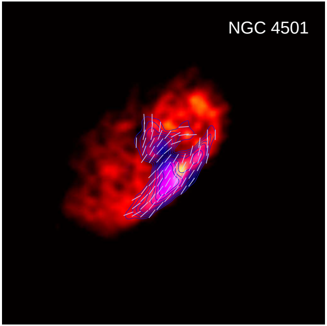
$$\gamma = \left(\frac{2\pi\nu_{\rm syn} m_{\rm e} c}{3eB}\right)^{1/2} \simeq 10^4 \left(\frac{\nu_{\rm syn}}{5\,\rm GHz}\right)^{1/2} \left(\frac{B}{7\,\mu\rm G}\right)^{-1/2},$$

$$\tau_{\rm syn} = \frac{6\pi m_{\rm e} c}{\sigma_{\rm T} B^2 \gamma} \simeq 50\,\rm Myr \left(\frac{\nu_{\rm syn}}{5\,\rm GHz}\right)^{-1/2} \left(\frac{B}{7\,\mu\rm G}\right)^{-3/2},$$

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

with velocity in draping layer $v_{\rm drape} \simeq 100\,\rm km\,s^{-1}$ and a geometric factor $\eta \simeq 2$.

Conclusions on magnetic draping around galaxies



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

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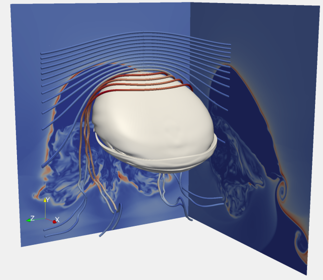

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- this represents a new tool for measuring the in situ 3D orientation and coherence scale of cluster magnetic fields

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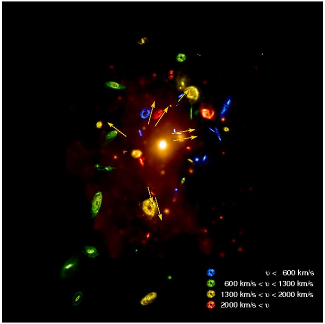

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- application to the Virgo cluster shows that the magnetic field is preferentially aligned radially

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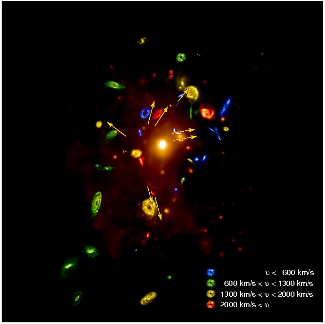

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- this finding implies efficient thermal conduction across clusters
  → thermal cluster history & cluster cosmology
- great prospects for LOFAR observations:
  uncovering the history of the magnetic drape

Literature for the talk

- Pfrommer & Dursi, 2010, Nature Phys., 6, 5206, *Detecting the orientation of magnetic fields in galaxy clusters*
- Dursi & Pfrommer, 2008, ApJ, 677, 993, *Draping of cluster magnetic fields over bullets and bubbles - morphology and dynamic effects*

Magneto-thermal instability: the idea

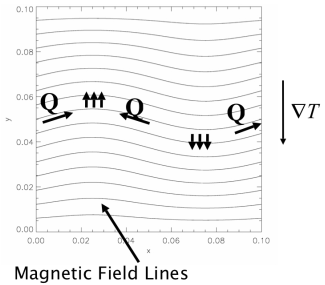


Figure from I. Parrish

Convective stability in a gravitational field:

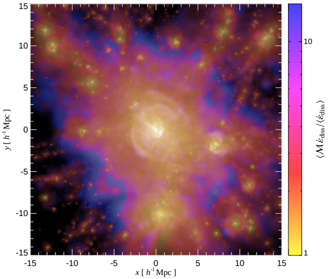
- Classical Schwarzschild criterion: $\frac{dS}{dz} > 0$
- long MFP, Balbus criterion: $\frac{dT}{dz} > 0$
- new instability causes field lines to reorient radially $\rightarrow$ efficient thermal conduction radially (close to Spitzer)

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

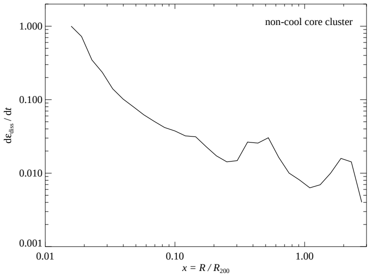
- Adiabatic boundary conditions for $T(r)$: the instability can exhaust the source of free energy $\rightarrow$ isothermal profile
- Fixed boundary conditions for $T(r)$: field lines stay preferentially radially aligned (35 deg mean deviation from radial)

Gravitational shock wave heating

Observed temperature profile in clusters is decreasing outwards
$\rightarrow$ heat also flows outwards along the radial magnetic field.
How is the temperature profile maintained? $\rightarrow$ gravitational heating



shock strengths weighted by dissipated energy



energy flux through shock surface $\dot{E}_{\rm diss}/R^2 \sim \rho \upsilon^3$
$\rightarrow$ increase towards the center