Detecting the orientation of magnetic fields in galaxy clusters

Christoph Pfrommer[1]

in collaboration with

Jonathan Dursi[1,2]

[1] Canadian Institute for Theoretical Astrophysics, Canada
[2] SciNet Consortium, University of Toronto, Canada

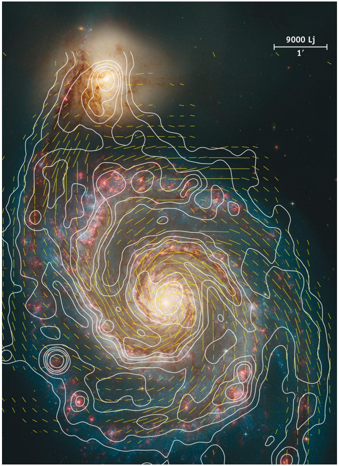
Jul 28, 2010 / Galaxy Clusters, Garching

CITA–ICAT

Outline

1. Magnetic draping on spiral galaxies
    - Polarized radio ridges
    - Physics of magnetic draping
    - Draping and synchrotron emission
2. Implications and speculations
    - Magnetic field orientations
    - Kinetic plasma instabilities
    - Cosmological evolution of galaxy clusters
3. Conclusions

Polarized synchrotron emission in a field spiral: M51

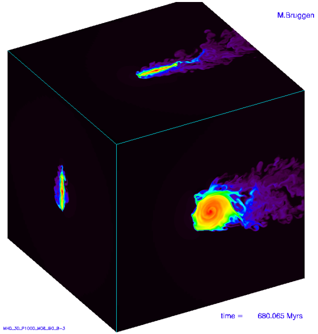


MPIfR Bonn and Hubble Heritage Team

- polarized synchrotron intensity follows the spiral pattern and is strongest in between the spiral arms (NGC 6946)
- the polarization ‘B-vectors’ are aligned with the spiral structure
- a promising generating mechanism is the *dynamo which transfers mechanical into magnetic energy* (Beck et al. 1996)

CITA–ICAT

Ram-pressure stripping of cluster spirals



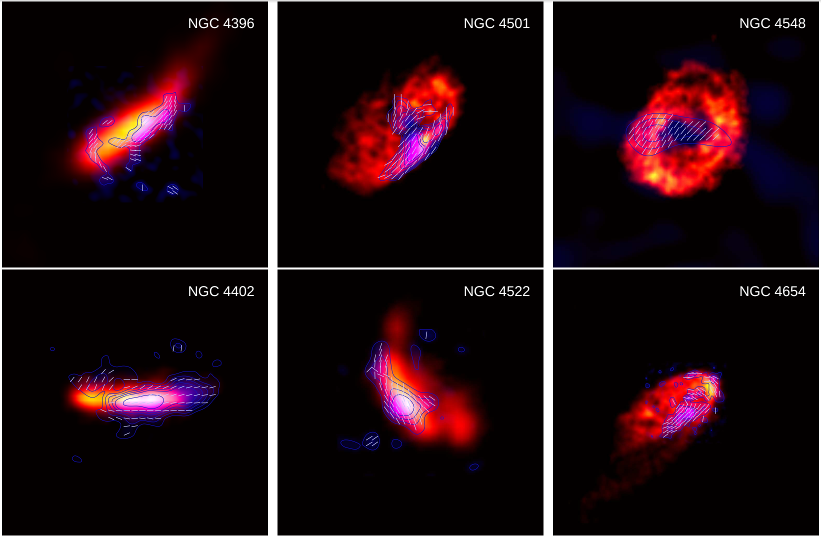
Brueggen (2008)

- 3D hydrodynamical simulations show that low-density gas in between spiral arms is quickly stripped irrespective of disk radius (Tonnesen & Bryan 2010)
- being flux-frozen into this dilute plasma, the large scale field will also be stripped, leaving behind the small scale field in the star forming regions

→ beam depolarization effects and superposition of causally unconnected star forming patches along the line-of-sight cause the resulting radio synchrotron emission to be effectively unpolarized

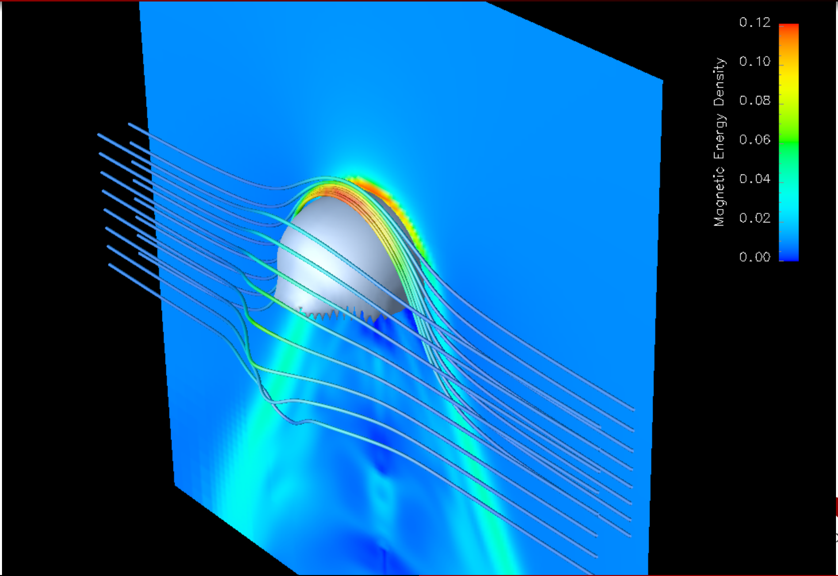
CITA–ICAT

Polarized synchrotron ridges in Virgo spirals

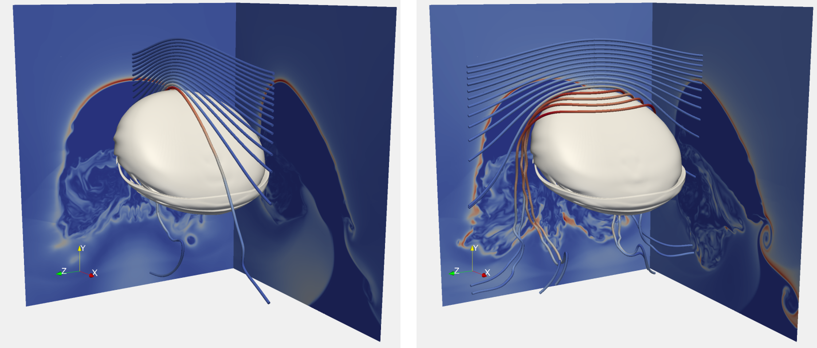


Vollmer et al. (2007): 6 cm PI (contours) + B-vectors; Chung et al. (2009): HI (red)

Draping field lines around a moving object

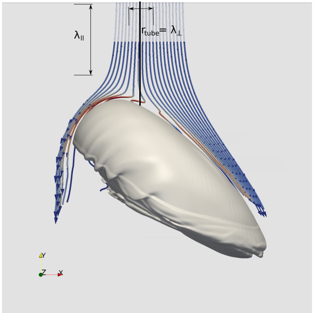


Magnetic draping around a spiral galaxy – MHD



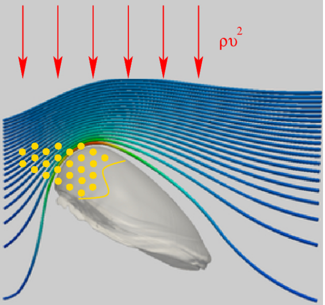
Athena simulations of spiral galaxies interacting with a uniform cluster magnetic field. There is a sheath of strong field draped around the leading edge (field strength is color coded).

Streamlines in the rest frame of the galaxy



- as the flow approaches the galaxy it decelerates and gets deflected
- only those streamlines initially in a narrow tube of radius $\lambda_\perp \simeq R/\sqrt{3\beta\mathcal{M}^2} \simeq R/15 \simeq 1.3$ kpc from the stagnation line become part of the magnetic draping layer (color coded) → 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

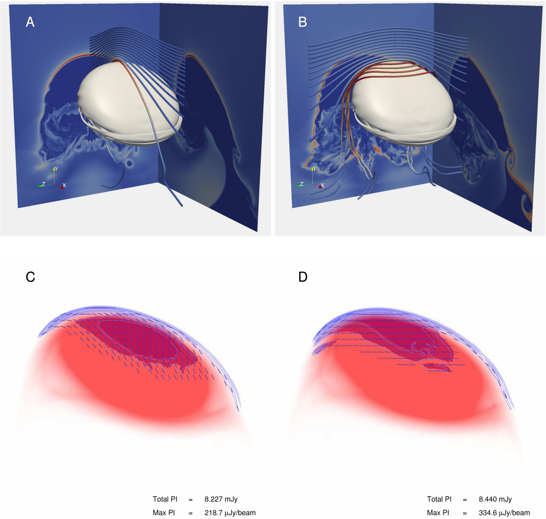
Magnetic draping around a spiral galaxy – physics



- the galactic ISM is pushed back by the ram pressure wind $\sim \rho \upsilon^2$
- the stars are largely unaffected and lead the gas
- the draping sheath is formed at the contact of ISM/ICM
- 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

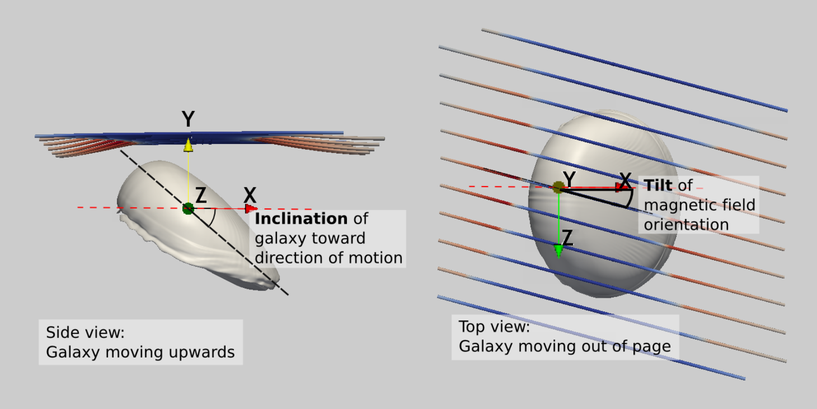
Magnetic draping and polarized synchrotron emission

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

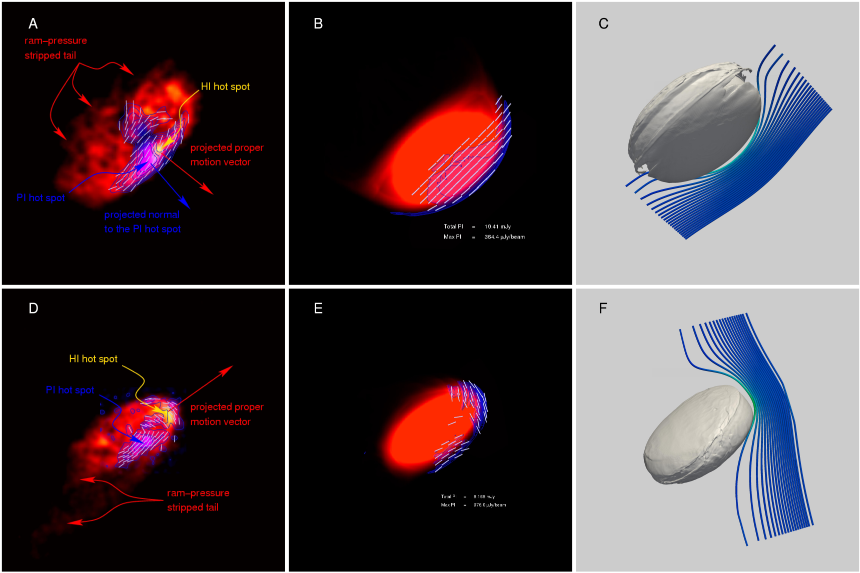


CITA–ICAT

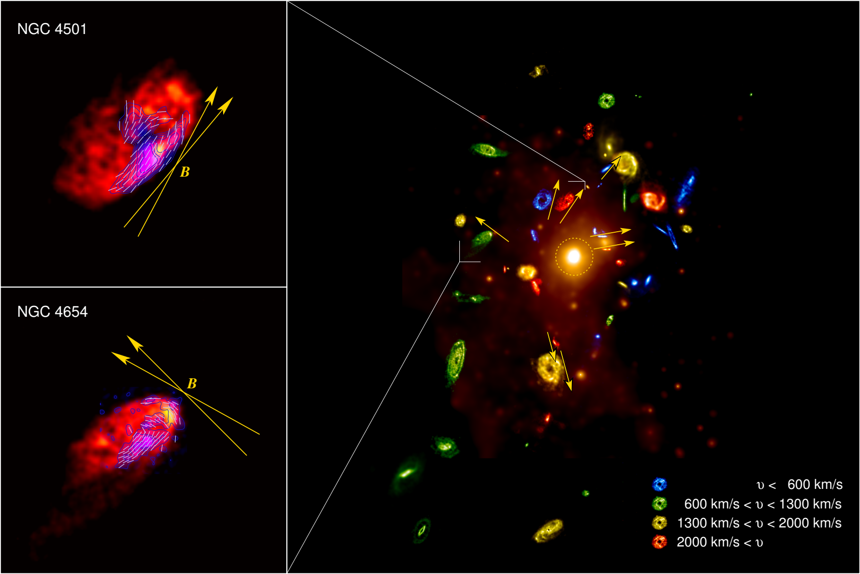
Varying galaxy inclination and magnetic tilt



Observations versus simulations



Mapping out the magnetic field in Virgo



Magneto-thermal instability: the idea

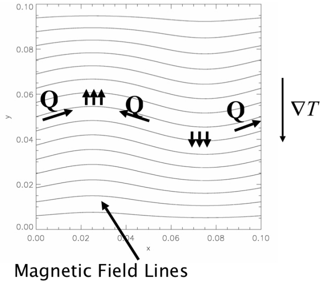


Figure from I. Parrish

Convective stability in a gravitational field:

- Classical Schwarzschild criterion: $\frac{\mathrm{d}S}{\mathrm{d}z} > 0$
- long MFP, Balbus criterion: $\frac{\mathrm{d}T}{\mathrm{d}z} > 0$
- 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)

Magneto-thermal instability: the idea

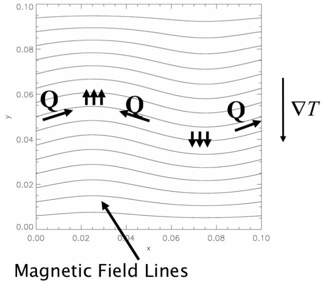


Figure from I. Parrish

Convective stability in a gravitational field:

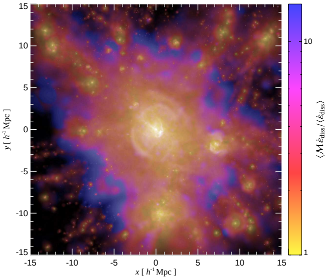
- Classical Schwarzschild criterion: $\frac{\mathrm{d}S}{\mathrm{d}z} > 0$
- long MFP, Balbus criterion: $\frac{\mathrm{d}T}{\mathrm{d}z} > 0$
- new instability causes field lines to reorient radially → efficient thermal conduction radially (close to Spitzer)

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

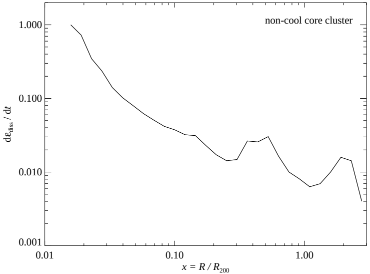
- Adiabatic boundary conditions for $T(r)$: the instability can exhaust the source of free energy → isothermal profile
- Fixed boundary conditions for $T(r)$: field lines stay preferentially radially aligned (35 deg mean deviation from radial)

Gravitational shock wave heating

The observed temperature profile in clusters is decreasing outwards which is the necessary condition for MTI to operate → *gravitational heating can stabilize the temperature profile:*



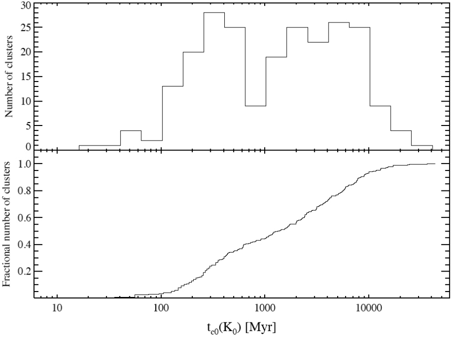
Mach number distribution weighted by $\varepsilon_{\rm diss}$.



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

CITA–ICAT

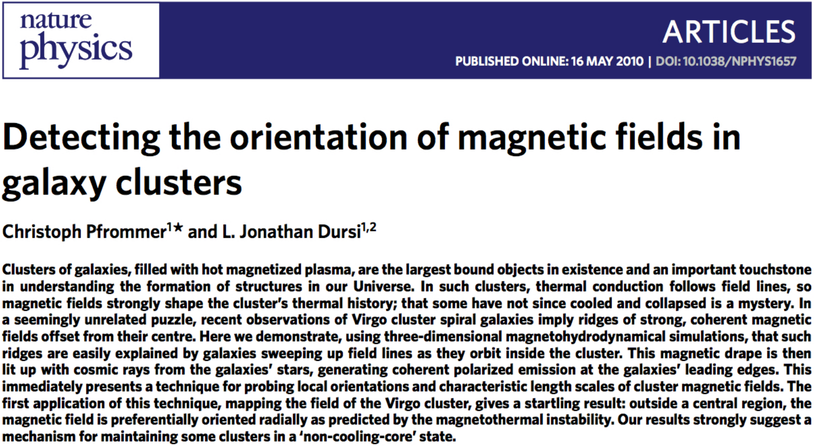
Implications for thermal stability of galaxy clusters



Cavagnolo et al. (2009)

- radial fields in non-cool core clusters (NCCs) imply efficient thermal conduction that stabilizes these systems against entering a cool-core state: $\tau_{\rm cond} = \lambda^2/\chi_{\rm C} \simeq 2.3 \times 10^7\,{\rm yr}\,(\lambda/100\,{\rm kpc})^2$, where $\chi_{\rm C}$ is the Spitzer thermal diffusivity (using $kT = 10\,{\rm keV}$, $n = 5 \times 10^{-3}\,{\rm cm}^{-3}$)
- current cosmological cluster simulations fail to reproduce NCCs that have no AGN activity → MHD + anisotropic conduction

Magnetic draping at spiral galaxies in the Virgo cluster



nature physics

ARTICLES

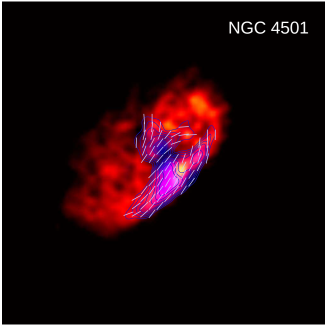
PUBLISHED ONLINE: 16 MAY 2010 | DOI: 10.1038/NPHYS1657

Detecting the orientation of magnetic fields in galaxy clusters

Christoph Pfrommer[1]* and L. Jonathan Dursi[1,2]

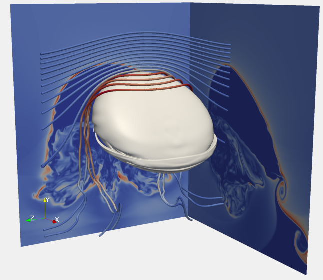
Clusters of galaxies, filled with hot magnetized plasma, are the largest bound objects in existence and an important touchstone in understanding the formation of structures in our Universe. In such clusters, thermal conduction follows field lines, so magnetic fields strongly shape the cluster's thermal history; that some have not since cooled and collapsed is a mystery. In a seemingly unrelated puzzle, recent observations of Virgo cluster spiral galaxies imply ridges of strong, coherent magnetic fields offset from their centre. Here we demonstrate, using three-dimensional magnetohydrodynamical simulations, that such ridges are easily explained by galaxies sweeping up field lines as they orbit inside the cluster. This magnetic drape is then lit up with cosmic rays from the galaxies' stars, generating coherent polarized emission at the galaxies' leading edges. This immediately presents a technique for probing local orientations and characteristic length scales of cluster magnetic fields. The first application of this technique, mapping the field of the Virgo cluster, gives a startling result: outside a central region, the magnetic field is preferentially oriented radially as predicted by the magnetothermal instability. Our results strongly suggest a mechanism for maintaining some clusters in a 'non-cooling-core' state.

Conclusions on magnetic draping around galaxies



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

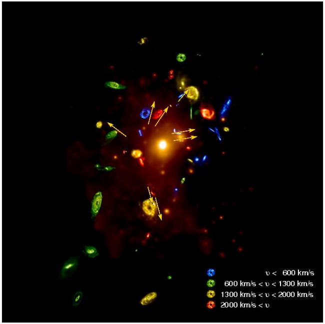
Conclusions on magnetic draping around galaxies



- draping of cluster magnetic fields naturally explains polarization ridges at Virgo spirals
- this represents a new tool for measuring the in situ orientation and coherence scale of cluster magnetic fields

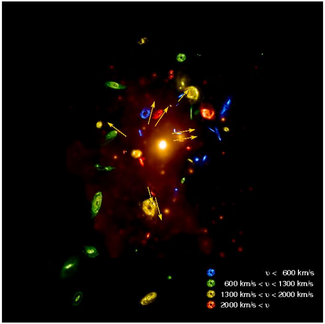
CITA–ICAT

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 orientation and coherence scale of cluster magnetic fields
- application to the Virgo cluster shows that the magnetic field is preferentially aligned radially

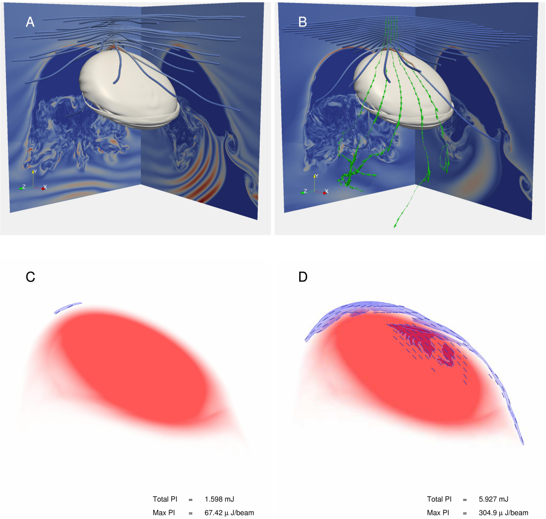
Conclusions on magnetic draping around galaxies



- draping of cluster magnetic fields naturally explains polarization ridges at Virgo spirals
- this represents a new tool for measuring the in situ orientation and coherence scale of cluster magnetic fields
- application to the Virgo cluster shows that the magnetic field is preferentially aligned radially
- this finding is suggestive that the MTI may be operating and implies efficient thermal conduction close to the Spitzer value
- it also proposes that non-cool core clusters are stabilized by thermal conduction

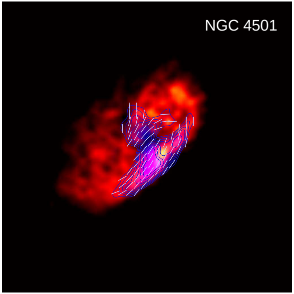
Magnetic draping of a non-uniform B-field

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



CITA–ICAT

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

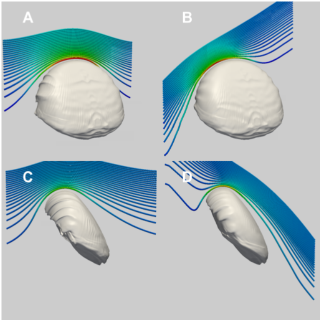
$$L_{\rm coh} \simeq \eta L_{\rm drape} v_{\rm gal}/v_{\rm drape} = \eta \tau_{\rm syn} v_{\rm gal} > 100\,{\rm kpc},$$

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

CITA–ICAT

Biases in inferring the field orientation

- uncertainties in estimating the 3D velocity: v_r, ram-pressure stripped gas visible in HI morphology → $\hat{\boldsymbol{v}}_\mathrm{t}$
- *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) → maximum polarised intensity may bias the location of $B_\mathrm{max,\,drape}$ towards the location in the drape with large B_t