Magnetic draping – from space physics to galaxy clusters and cosmology

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June 7 – 11, 2010 / Cosmic Magnetism, Kiama, Australia

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Outline

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1. Magnetic draping
   - Physics
   - Solar system
   - Galaxy clusters
2. Spiral galaxies
   - Polarized radio ridges
   - Draping and synchrotron emission
   - Magnetic coherence scale
3. Implications
   - Magnetic field orientations
   - Kinetic plasma instabilities
   - Cosmological evolution of galaxy clusters

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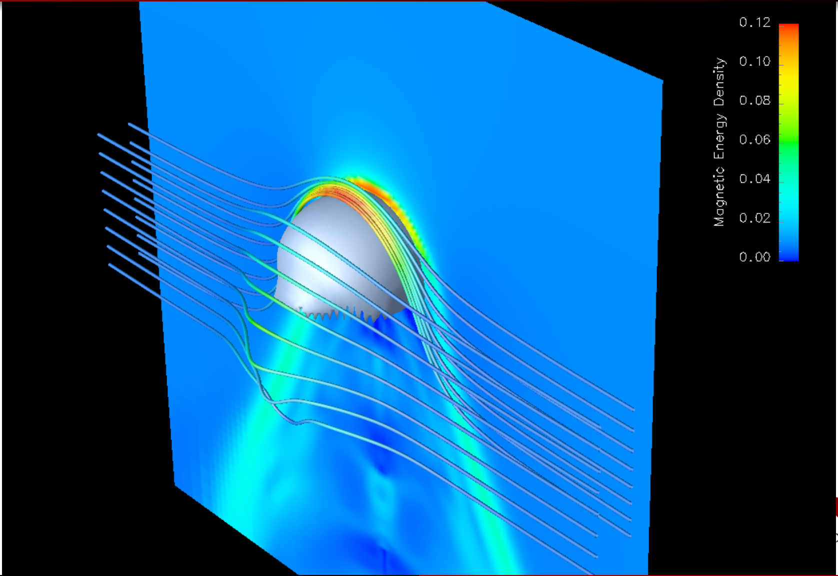
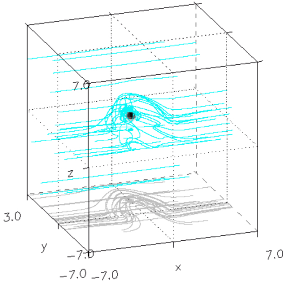
Draping field lines around a moving object



Draping of solar wind field around the Earth

- the Earth's dipolar field shields the surface from penetrating cosmic rays
- the magnetic dipole has reversed sign some hundreds of times over the last 400 million years, which may correspond to breakdowns of the dynamo action



Birk, Lesch & Konz (2004)

- 3D plasma-neutral gas simulations show that the solar wind can induce very fast ($\sim$10 min) a strong magnetic field in the previously completely unmagnetized Earth's ionosphere
- Earth magnetic polarity reversals may not be catastrophic to life!

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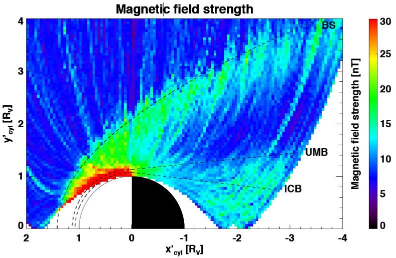
Draping of the interplanetary field over Venus

- Venus and Mars do not have a global magnetic field
- *right:* spatial distribution of the magnetic field strength in the plasma environment surrounding Venus (Venus Express)



Guicking et al. (2010)

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

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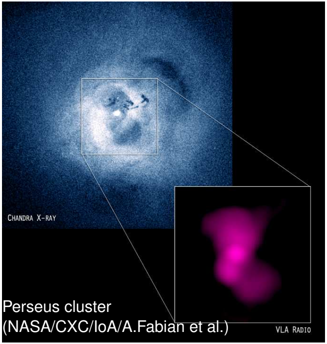
Puzzles in galaxy clusters

- radio bubbles, seen as X-ray cavities, are observed out to large distances and have very sharp interfaces: hydrodynamic instabilities should disrupt them
- high-resolution X-ray data reveal ‘cold fronts’ with sharp edges in temperature and density: they are not expected to remain sharp in the presence of diffusion and thermal conduction for $\gtrsim 10^8$ yrs



Perseus cluster
(NASA/CXC/IoA/A.Fabian et al.)

→ Could bubble/core motions sweep up enough magnetic field to suppress instabilities and diffusion/conduction across the interface?

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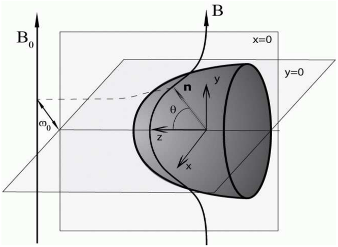
Idea: magnetic draping comes to rescue (Lyutikov 2004)

- analytics, B-profile along the stagnation line:

$$\frac{B}{\rho} = \frac{1}{\sqrt{1-\frac{R^3}{r^3}}}\,\frac{B_0}{\rho_0}, \qquad l_{\rm drape} \approx \frac{1}{\mathcal{M}_A^2}\,R$$

- formula predicts infinite B-amplification at the contact that is in conflict with the kinematic assumption of negligible back-reaction



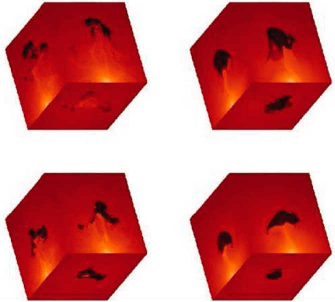
Lyutikov (2004)

→ need MHD simulations to account for the non-linear feedback!

Magnetic draping at radio bubbles

- rising radio bubbles in a hot atmosphere
- shown is the log of the density for the non-draping versus draping case (time increasing upwards)

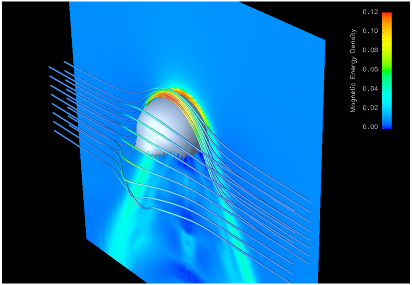
  $\rightarrow$ draping suppresses hydrodynamical instabilities in accordance with observations



Ruszkowski et al. (2007)

Magnetic draping at cold fronts

- dense core of a merging cluster performs sloshing motions in the bottom of the larger clusters' potential well
- unavoidable draping of a dynamically strong magnetic layer around the contact surface



Dursi & C.P. (2008)

- draped magnetic field suppresses diffusion/conduction across the interface → sharp density/temperature edges!

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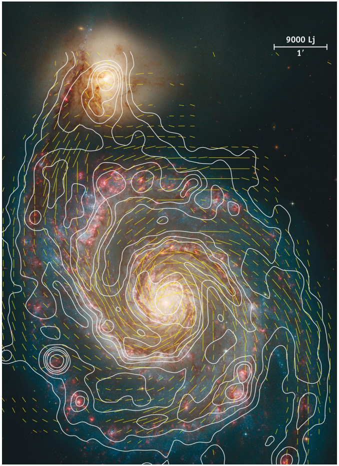
Polarized synchrotron emission in a field spiral: M51



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)
- efficient dynamo needs turbulent motions and non-uniform (differential) rotation of the disk

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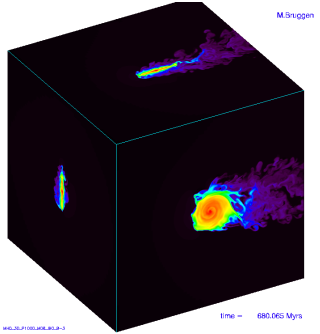
Ram-pressure stripping of cluster spirals

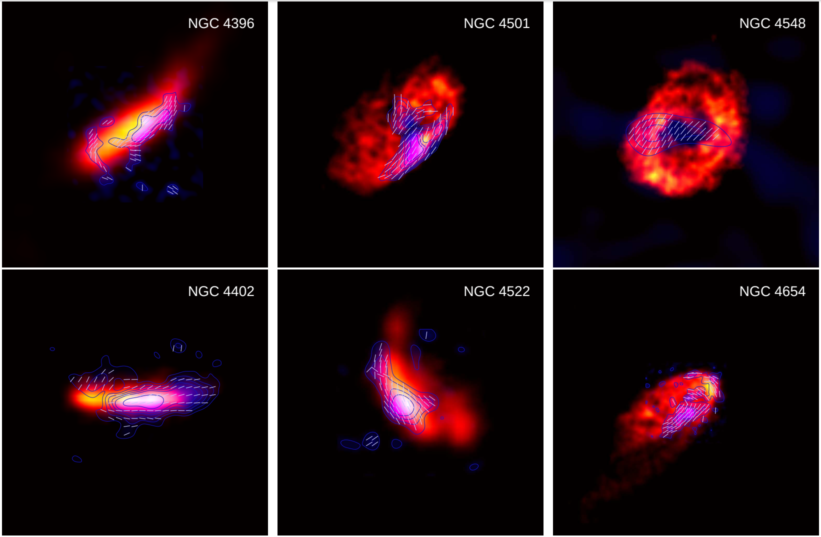


Brueggen (JU Bremen)

- 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

$\longrightarrow$ 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

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 ~ 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

→ previous models that use ram-pressure compressed galactic magnetic fields fail to explain most of these points!

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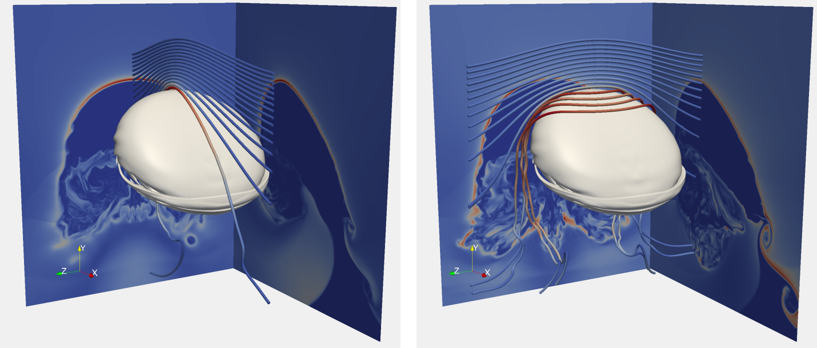
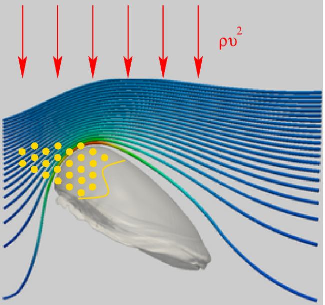
$\rightarrow$ need to consider the full MHD of the interaction spiral galaxy and magnetized ICM !

Magnetic draping around a spiral galaxy – 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).

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 $\rightarrow$ coherent polarized emission at the galaxies' leading edges

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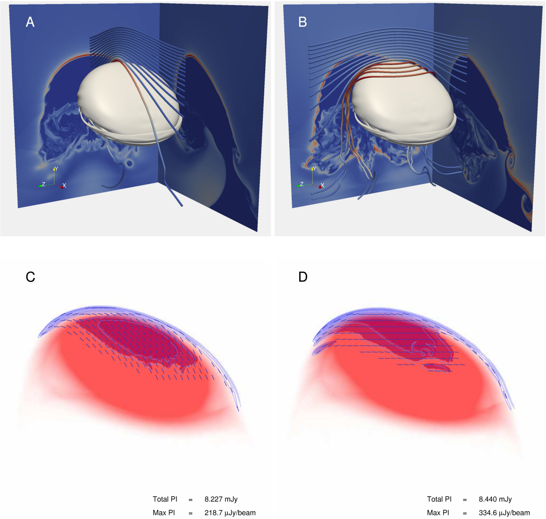
Magnetic draping and polarized synchrotron emission

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



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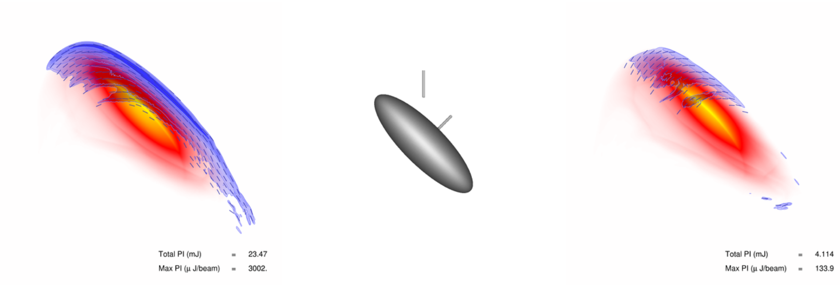
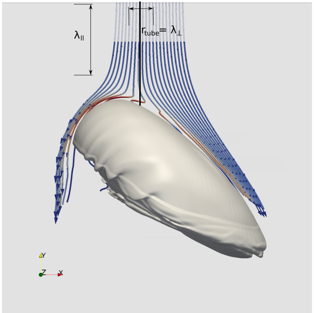
Simulated polarized synchrotron emission



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

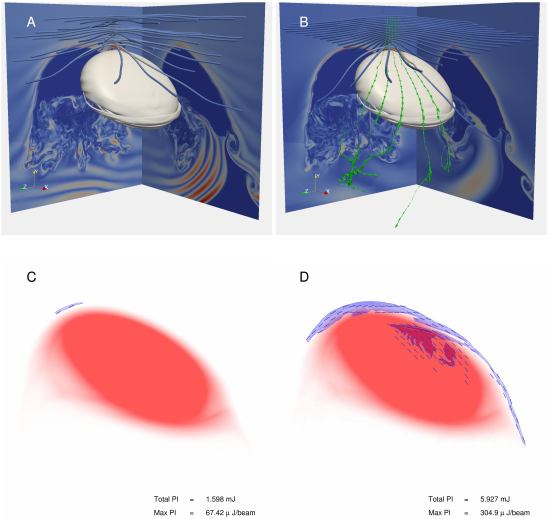
Streamlines in the rest frame of the galaxy



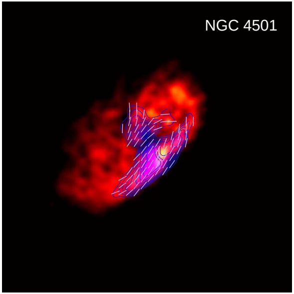
- as the flow approaches the galaxy it decelerates and gets deflected
- only those streamlines initially in a narrow tube of radius $\lambda_{\perp} \simeq R/\sqrt{3\beta\mathcal{M}^2} \simeq R/15 \simeq 1.3$ kpc from the stagnation line become part of the magnetic draping layer (color coded) $\rightarrow$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

Magnetic draping of a non-uniform 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 $\eta \simeq 2$

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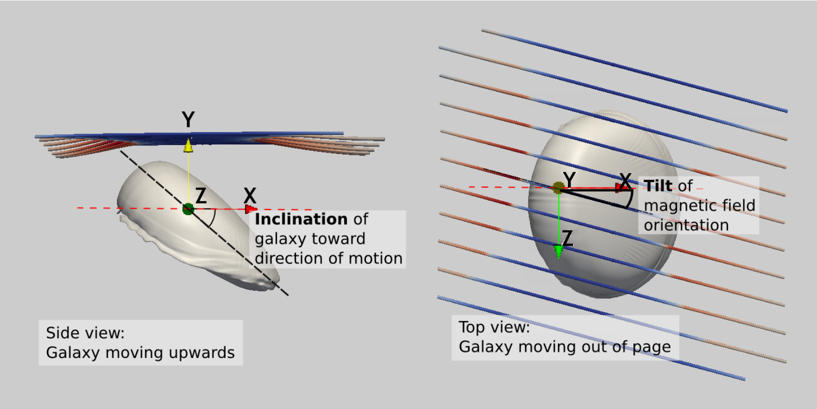
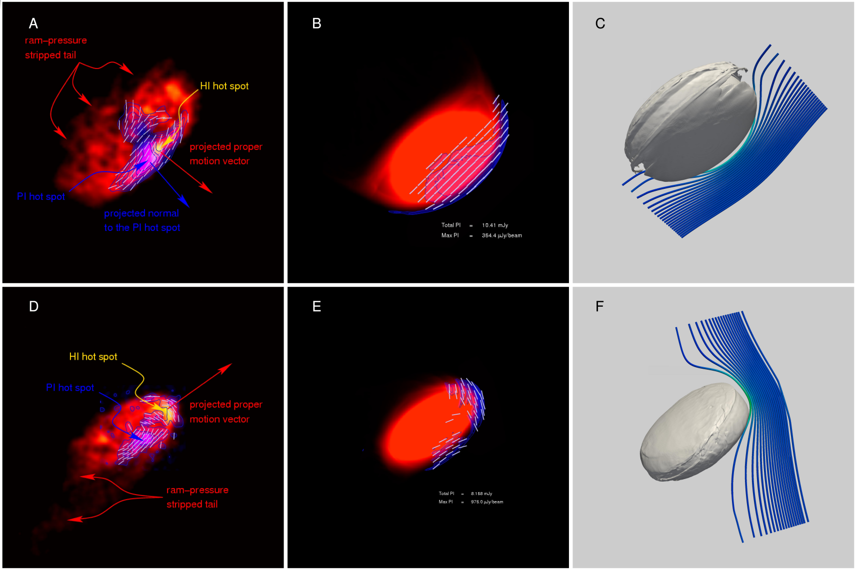
Varying galaxy inclination and magnetic tilt

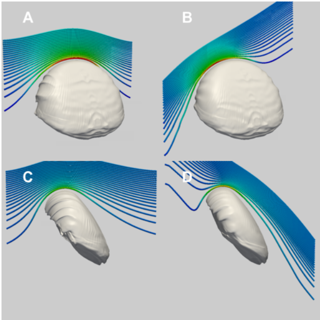


Observations versus simulations



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

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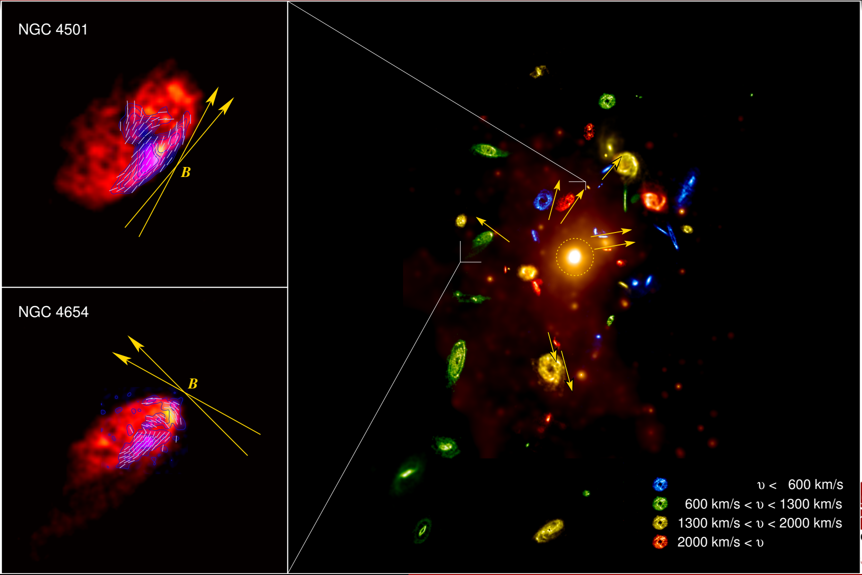
Mapping out the magnetic field in Virgo



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% ($\sim 2.2\,\sigma$).[1]
- For the three nearby galaxy pairs in the data set, all have very similar field orientations.
- The isotropic distribution with respect to the centre (M87) is difficult to explain with the past activity of the central AGN.

$\rightarrow$ Which effect causes this field geometry?

[1] Caveat: this statistical analysis does not include systematic uncertainties such as line-of-sight effects.

Magneto-thermal instability: the idea

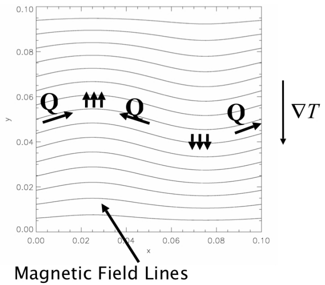


Figure from I. Parrish

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 $\rightarrow$ 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)

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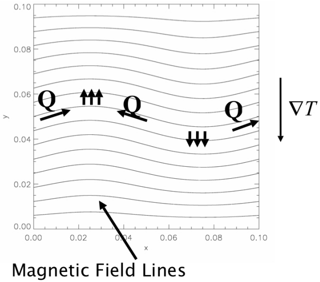

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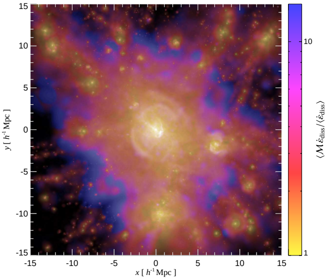
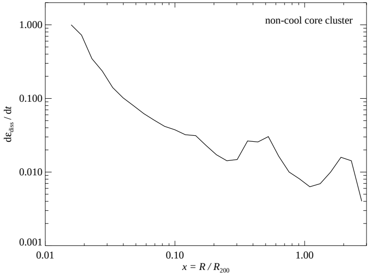
Gravitational shock wave heating

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:*

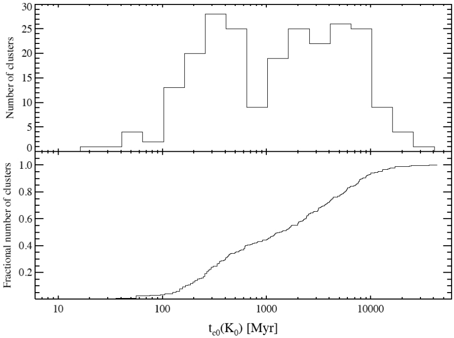


Mach number distribution weighted by $\varepsilon_{\mathrm{diss}}$.



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

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: $\tau_{\rm cond} = \lambda^2/\chi_{\rm C} \simeq 2.3 \times 10^7\,\mathrm{yr}\,(\lambda/100\,\mathrm{kpc})^2$, where $\chi_{\rm C}$ is the Spitzer thermal diffusivity (using $kT = 10\,\mathrm{keV}$, $n = 5 \times 10^{-3}\,\mathrm{cm}^{-3}$)
- current cosmological cluster simulations fail to reproduce NCCs that have no AGN activity $\rightarrow$ MHD + anisotropic conduction

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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 $\tau_\text{eddy} \simeq L_\text{eddy}/\upsilon_\text{turb} \sim 300\,\text{kpc}/(300\,\text{km}/\text{s}) \sim 1$ 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 feedback by an active galactic nuclei to be stabilized.

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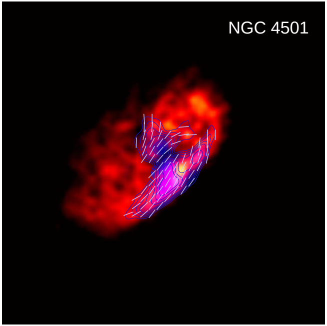
Conclusions on magnetic draping around galaxies



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

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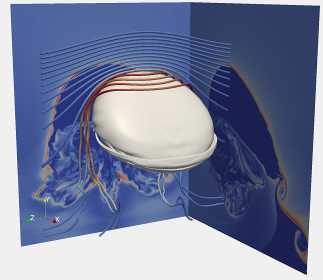

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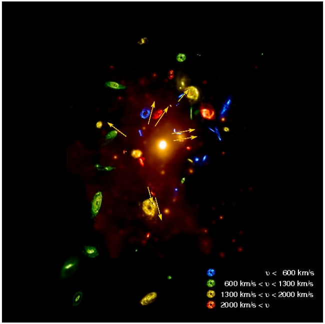

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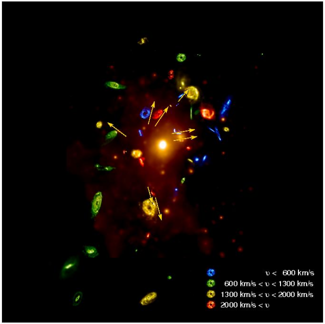

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- application to the Virgo cluster shows that the magnetic field is preferentially aligned radially

- 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

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Literature for the talk

- Pfrommer & Dursi, 2010, Nature Phys., published online, arXiv:0911.2476, *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*