Detecting the orientation of magnetic fields in galaxy clusters

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in collaboration with

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Outline

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   - 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

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Magnetic draping at spiral galaxies in the Virgo cluster

nature physics

ARTICLES

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Detecting the orientation of magnetic fields in galaxy clusters

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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.

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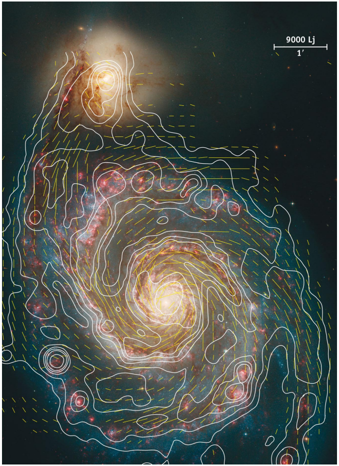
Polarized synchrotron emission in a field spiral: M51



MPIfR Bonn and Hubble Heritage Team

- polarized synchrotron intensity follows the spiral pattern and is strongest in between the spiral arms
- 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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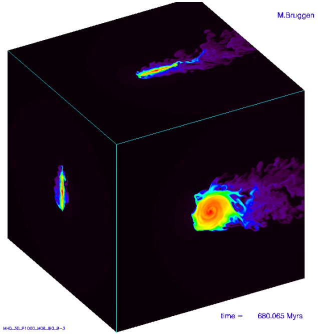
Ram-pressure stripping of cluster spirals



Brueggen & de Lucia (2008)

- 3D hydrodynamical simulations show that low-density gas in between spiral arms is quickly stripped irrespective of disk radius; it takes longer for the high-density gas (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

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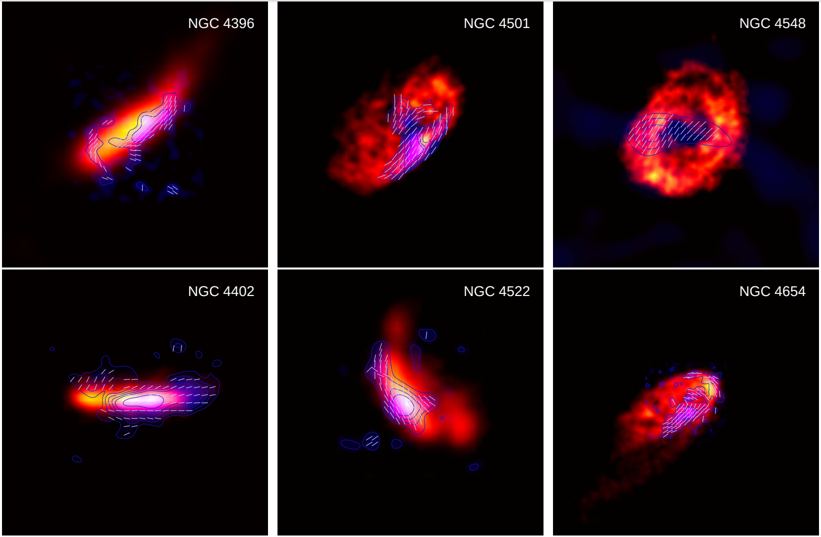
Polarized synchrotron ridges in Virgo spirals



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

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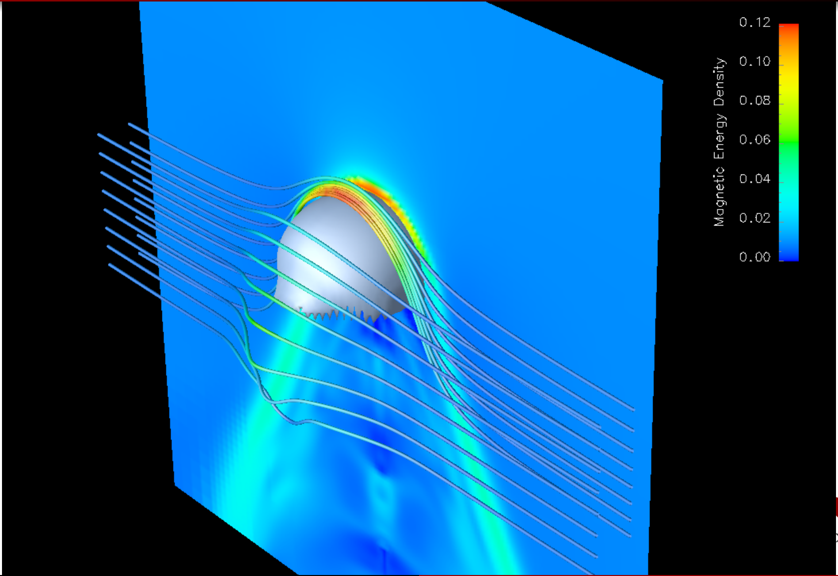
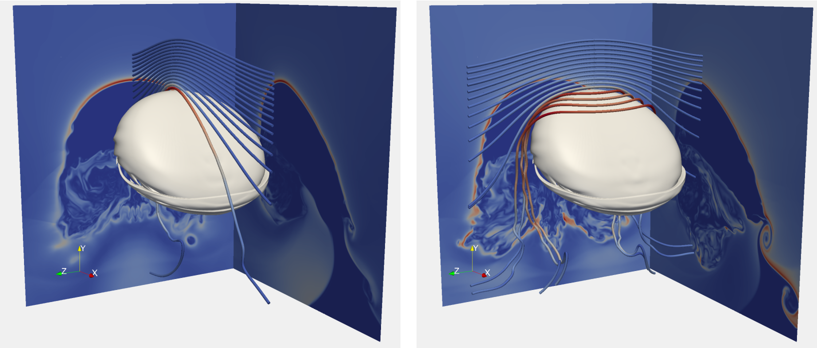
Draping field lines around a moving object

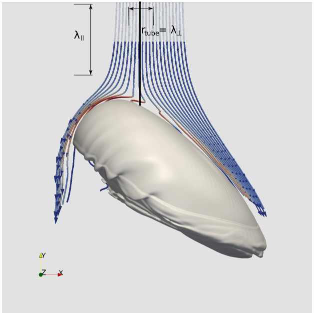


Magnetic draping around a spiral galaxy – MHD



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) $\rightarrow$ 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

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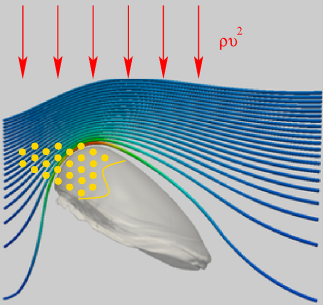
Magnetic draping around a spiral galaxy – physics



- 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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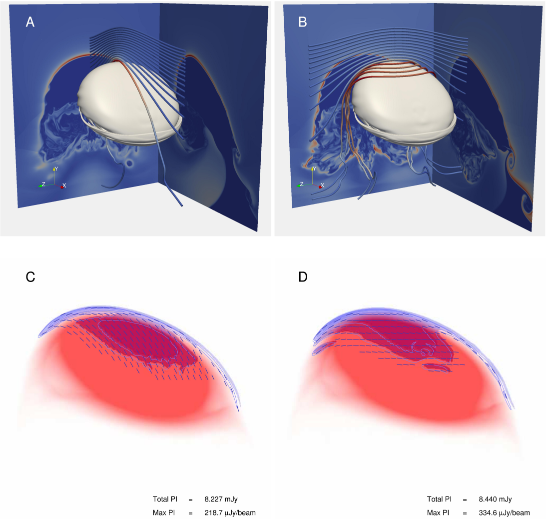
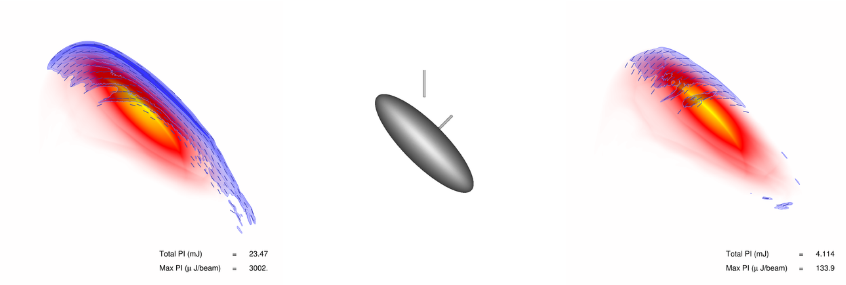
Magnetic draping and polarized synchrotron emission

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

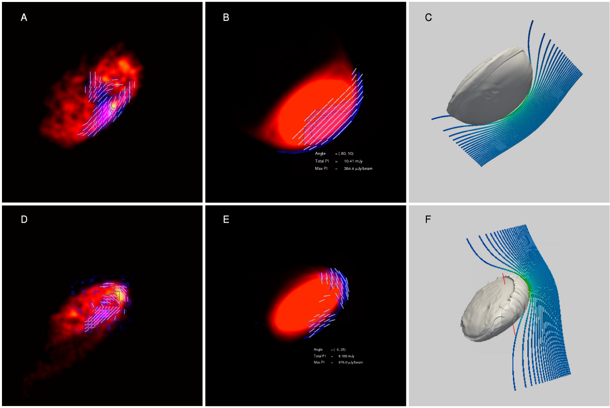


Simulated polarized synchrotron emission



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

Observations versus simulations



HI emission of two spirals (red) is compared to the polarized radio synchrotron ridges at 6 cm (blue and contours) and B-vectors.

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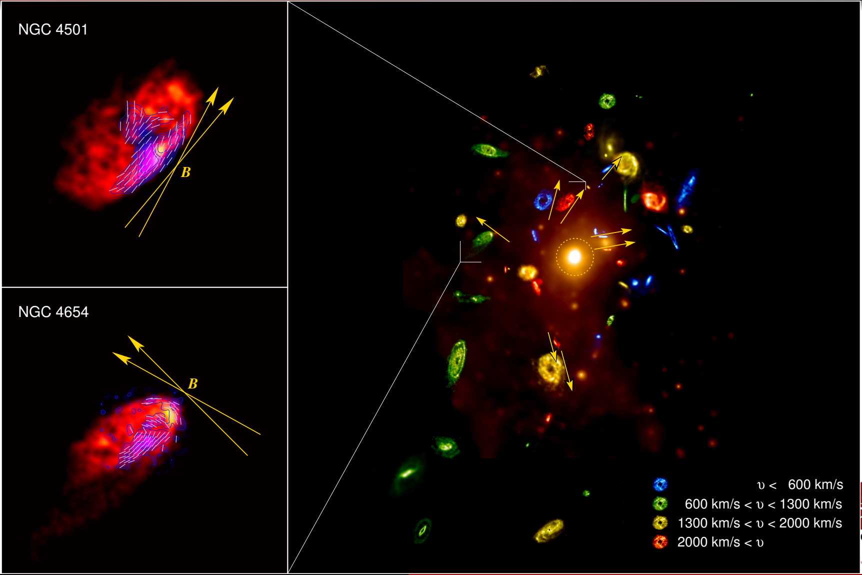
Mapping out the magnetic field in Virgo



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% ($\sim 2.2\,\sigma$).
- 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?

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Magneto-thermal instability: the idea

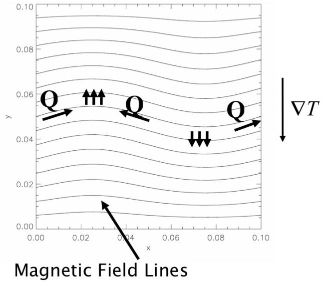

Figure from I. Parrish

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)

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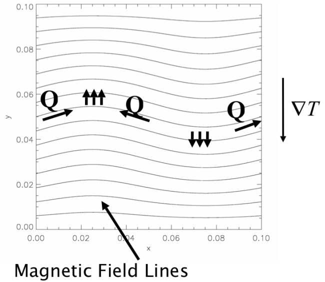

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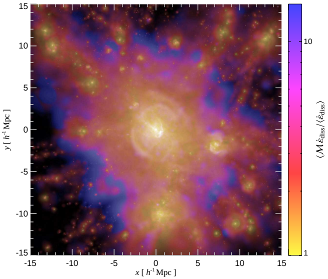
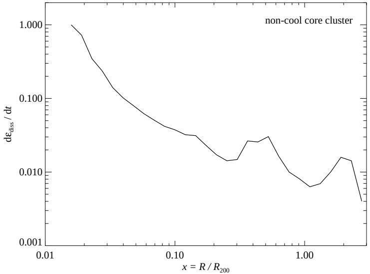
Gravitational shock wave heating

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 $\varepsilon_{\rm diss}$.



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

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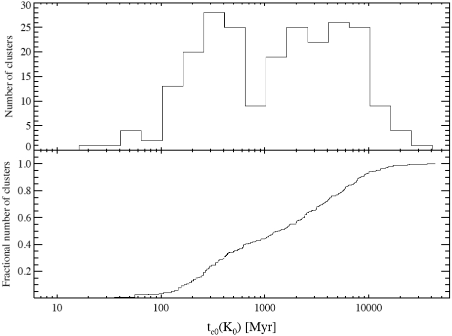
Implications for thermal stability of galaxy clusters



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: $\tau_\mathrm{cond} = \lambda^2/\chi_\mathrm{C} \simeq 2.3 \times 10^7\,\mathrm{yr}\,(\lambda/100\,\mathrm{kpc})^2$, where χ_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 → MHD + anisotropic conduction

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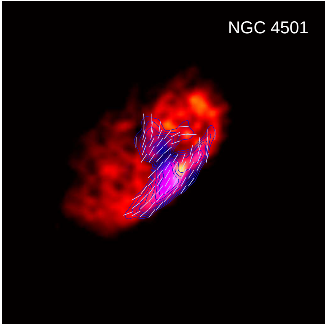
Conclusions on magnetic draping around galaxies



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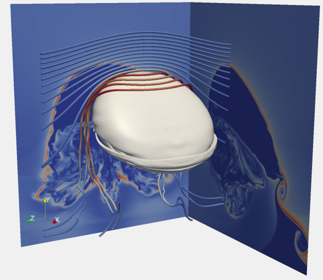

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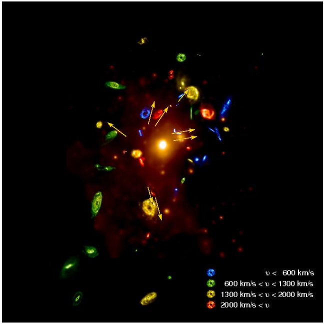

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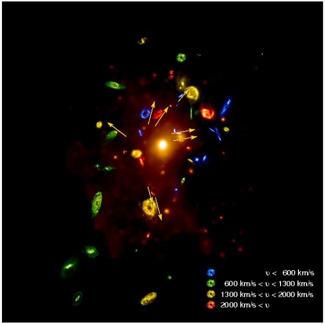

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- this represents a new tool for measuring the in situ 3D orientation and coherence scale of cluster magnetic fields
- application to the Virgo cluster shows that the magnetic field is preferentially aligned radially

- 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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