Uncovering the cloak of invisibility – Magnetic fields in the Universe

Christoph Pfrommer[1]

in collaboration with

Jonathan Dursi[2,3]

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

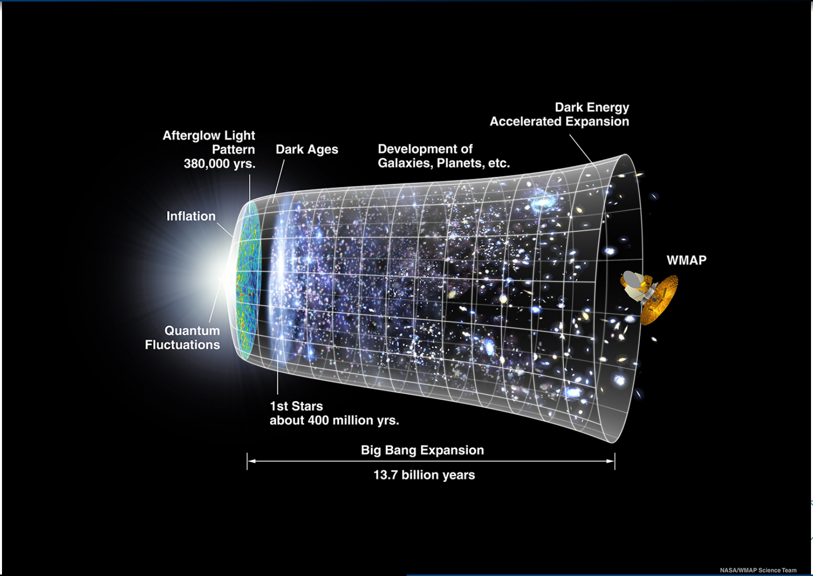
Feb 7, 2011 / HITS Scientific Seminar Series

Outline

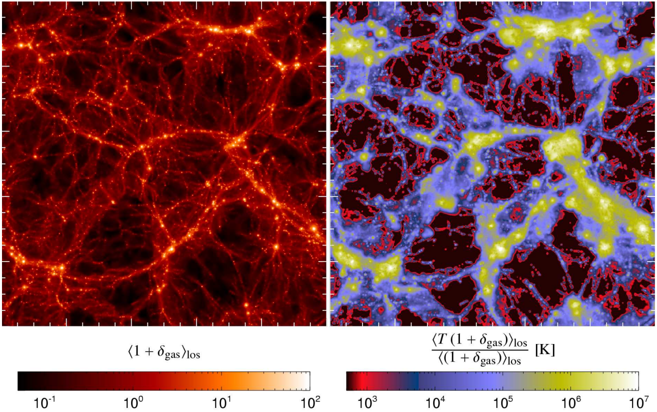
1. Astrophysical concepts
   - Galaxy clusters
   - Shock waves
   - Magnetic fields
2. Magnetic draping
   - Solar system
   - Spiral galaxies
   - Radio emission
3. Implications
   - Magnetic field orientations
   - Kinetic plasma instabilities
   - Evolution of galaxy clusters

Outline

Timeline of our Universe

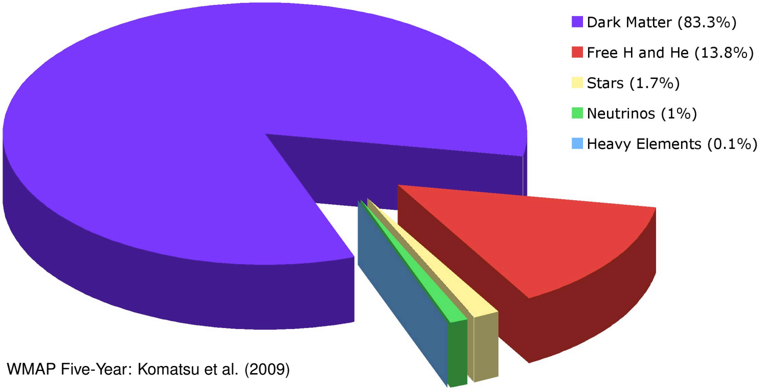


The structure of our Universe



The "cosmic web" today. *Left:* the projected gas density in a cosmological simulation. *Right:* gravitationally heated intracluster medium through cosmological shock waves (C.P. et al. 2006).

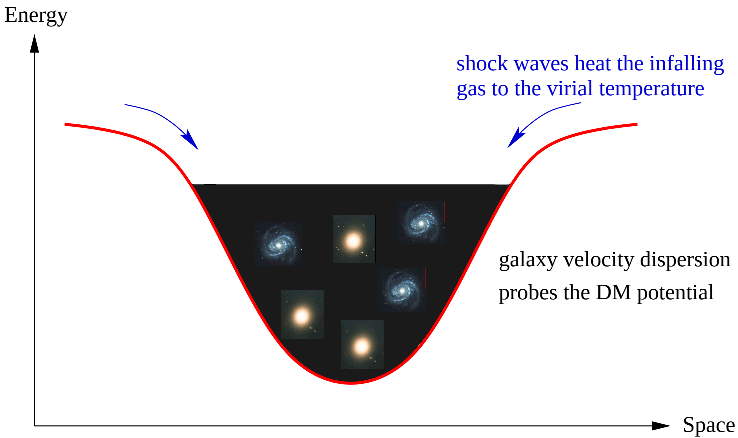
The matter content of the Universe / a galaxy cluster



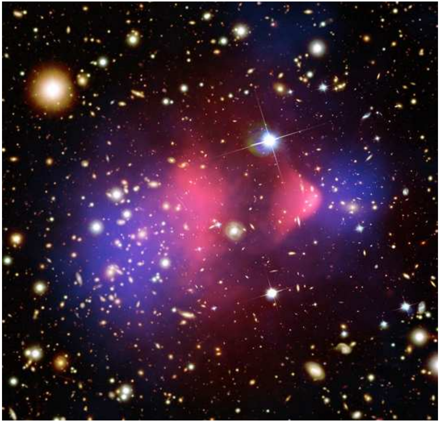
WMAP Five-Year: Komatsu et al. (2009)

A theorist's perspective of a galaxy cluster . . .

Galaxy clusters are dynamically evolving dark matter potential wells:

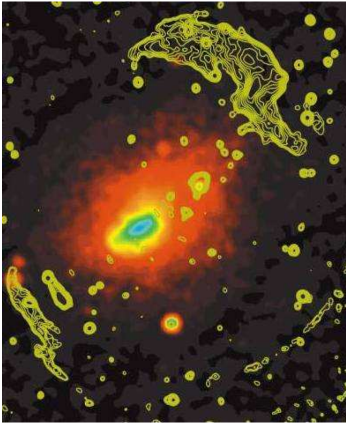


. . . and how the observer's Universe looks like



1E 0657-56 ("Bullet cluster")

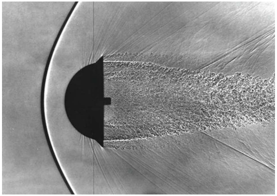
(X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.)



Abell 3667

(radio: Johnston-Hollitt. X-ray: ROSAT/PSPC.)

Shock waves



shock waves: sudden change in density, temperature, and pressure that decelerates supersonic flow.

thickness$\sim$ mean free path $\lambda_{\rm mfp}$

in air, $\lambda_{\rm mfp} \sim \mu$m,
on Earth, most shocks are mediated by collisions.

Mean free path to Coulomb collisions is huge:

$\lambda_{\rm mfp} \sim L_{\rm cluster}/10, \qquad \lambda_{\rm mfp} \sim L_{\rm SNR}$

Mean free path $\gg$ scales of interest!

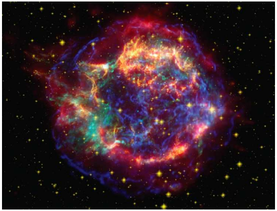
$\rightarrow$ shocks must be mediated without collisions, but through interactions with collective fields

$\rightarrow$ collisionless shocks

(slide concept Spitkovsky)

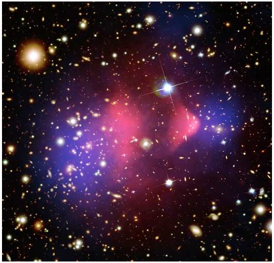
Shock waves

shock waves: sudden change in density, temperature, and pressure that decelerates supersonic flow.



thickness$\sim$ mean free path $\lambda_{\rm mfp}$

in air, $\lambda_{\rm mfp} \sim \mu$m,
on Earth, most shocks are mediated by collisions.



Mean free path to Coulomb collisions is huge:

$\lambda_{\rm mfp} \sim L_{\rm cluster}/10, \qquad \lambda_{\rm mfp} \sim L_{\rm SNR}$

Mean free path $\gg$ scales of interest!

$\rightarrow$ shocks must be mediated without collisions, but through interactions with collective fields

$\rightarrow$ collisionless shocks

(slide concept Spitkovsky)

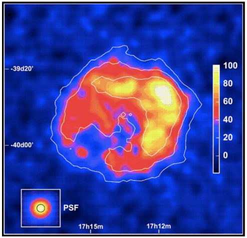
HITS

Shocks in supernova remnants

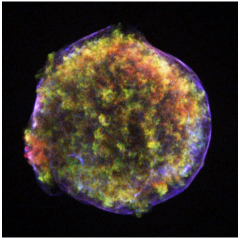
Astrophysical collisionless shocks can:

- accelerate particles (electrons and ions) $\rightarrow$ cosmic rays (CRs)
- amplify magnetic fields (or generate them from scratch)
- exchange energy between electrons and ions

SN 1006 X-rays (CXC/Hughes)



G347.3 HESS TeV (Aharonian et al. 2006)



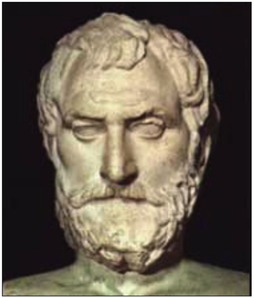
Tycho X-rays (CXC)

Magnetic fields

bar magnet & iron filings:

- iron is a ferromagnetic material
- magnetic field induces each filing to become a tiny bar magnet
- south pole of each filing attracts the north pole of its neighbors
- repetition over a wide area creates chains of filings parallel to the direction of the magnetic field

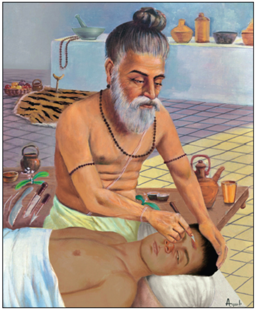
Historical magnetism



www.daviddarling.info

Thales of Miletus ($\sim$ 624 – $\sim$ 546 BCE):
"… the magnet has a soul in it because it moves the iron."
(Aristotle, *De Anima, 'on the soul'*)

Sushruta (Indian surgeon, $\sim$ 600 BCE):
"A loose, unbarbed arrow, lodged in a wound … should be withdrawn by applying a magnet to its end."
(Sushruta Samhita 27)



© Science-Scientists' Visuals

Mexican magnetism

- Sculpture of sea turtle with magnetic head, $\sim$ 300 BCE – 100 CE (Malmstrom 1076)

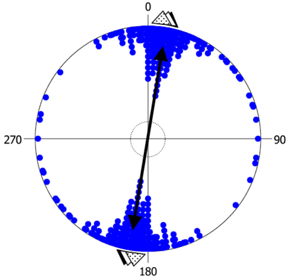
Malmstrom (1976)

- “Fat Boys”: magnetite sculptures with magnetic pole at temple or navel, $\sim$ 2000 BCE
- stone jaguar, magnetic poles in paws, $\sim$ 2000 BCE (Malmstrom 1997; Guimarães 2004)

authenticmaya.com

Biological magnetism

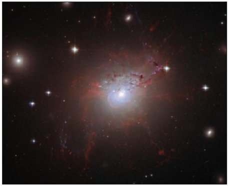
- Birds: retinal magneto-reception (Maeda et al. 2008; Mouritsen et al. 2004; Ritz et al. 2004)
- Roe deer: aligns with Earth's magnetic field when grazing or resting (Begall et al. 2008)
- Humans: bones in sinus contain ferric ion; duration of REM sleep depends on orientation with respect to Earth's magnetic field (Baker et al. 1983; Ruhenstroth-Bauer et al. 1987)

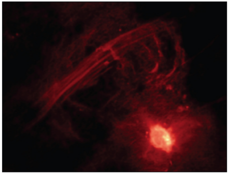


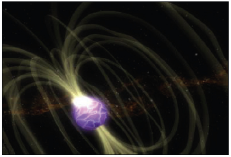
Begall et al. 2008

Extremes of cosmic magnetism

- High-z seed fields (Widrow 2002; Subramanian 2007) — $B \sim 10^{-30} - 10^{-20}$ G
- Intergalactic Medium — $B \sim$ 1-10 nG ?
- Intracluster Medium — $B \sim$ 0.1-1 μG
- Interstellar medium — $B \sim$ 1 μG – 10 mG
- Galactic Centre (Crocker et al. 2010; Ferrière 2010) — $B \sim$ 50 μG – 1 mG
- Main sequence star: HD 215441 (Babcock 1960) — $B_0 \approx$ 34 kG
- White dwarf: PG 1031+234 (Schmidt et al. 1986) — $B_0 \approx 10^9$ G
- Pulsar: PSR J1847-0130 (McLaughlin et al. 2003) — $B_0 \approx 9 \times 10^{13}$ G
- Magnetar: SGR 1806-20 (Kouveliotou et al. 1998, Israel et al. 2005) — $B_0 \approx 2 \times 10^{15}$ G, $B_i \approx 10^{16}$ G
- Cosmic strings (Ostriker et al. 1986) — $B \sim 10^{30}$ G
- Planck-mass monopoles (Duncan et al. 2000) — $B \sim 10^{55}$ G


Magnetic filaments in Perseus A (Fabian et al. 2008)


Galactic Centre (Yusef-Zadeh et al. 1984)


SGR 1806-20 giant flare (NASA)

(slide concept Gaensler)

Cosmic magnetic fields: the big questions

In recent years, we discovered the existence of magnetic fields on large scales but are pretty clueless about the following questions:

- Where do magnetic fields come from?
- How do they grow and evolve?
- What is their strength, structure, and topology?
- What implications have magnetic fields for ...
  - ... galaxy formation?
  - ... galaxy cluster evolution?
  - ... estimating cosmological parameters?

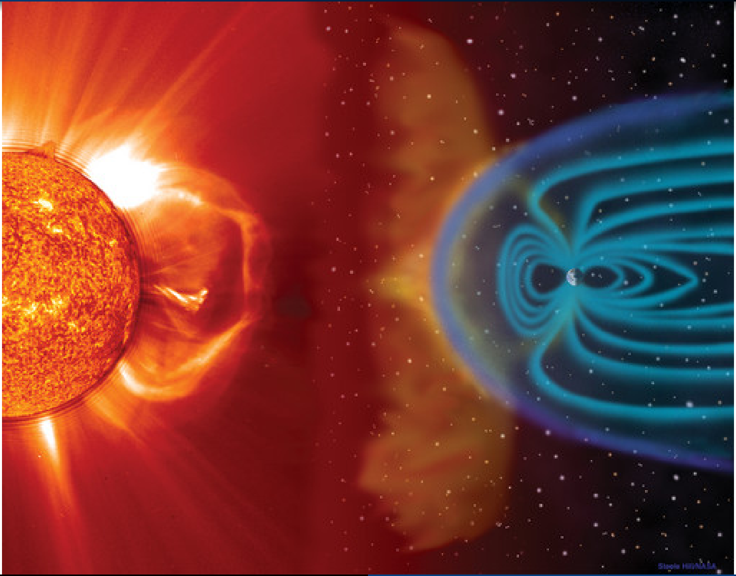
Cosmic magnetic fields: the big questions

In recent years, we discovered the existence of magnetic fields on large scales but are pretty clueless about the following questions:

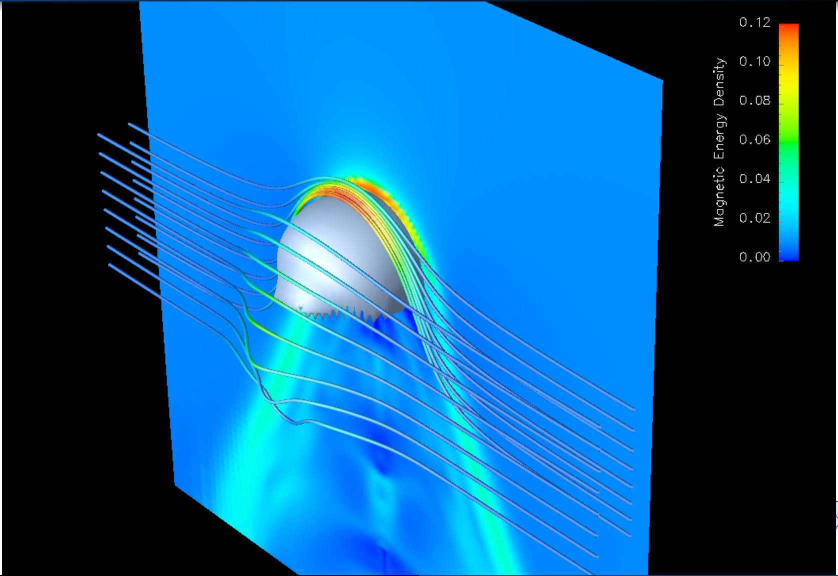
- Where do magnetic fields come from?
- How do they grow and evolve?
- What is their strength, structure, and topology?
- What implications have magnetic fields for . . .
  - . . . galaxy formation?
  - . . . galaxy cluster evolution?
  - . . . estimating cosmological parameters?

Outline

Magnetic field in the solar wind

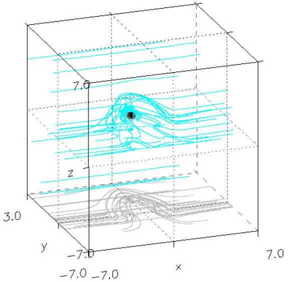


Draping field lines around a moving object



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



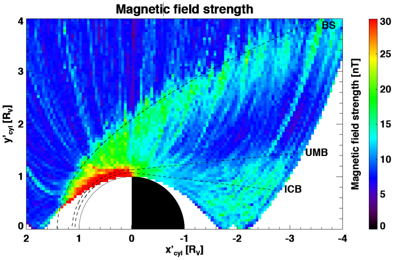
Birk, Lesch & Konz (2004)

- 3D plasma-neutral gas simulations show that the solar wind can induce very fast (∼10 min) a strong magnetic field in the previously completely unmagnetized Earth's ionosphere

→ Earth's magnetic polarity reversals may not be catastrophic to the biosphere!

Draping of the interplanetary field over Venus

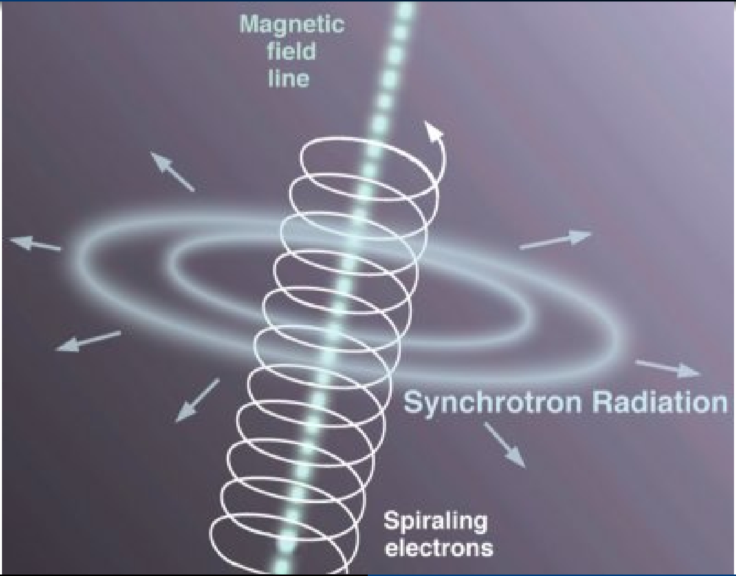
- Venus and Mars do not have a global magnetic field
- *right:* spatial distribution of the magnetic field strength in the plasma environment surrounding Venus (Venus Express)



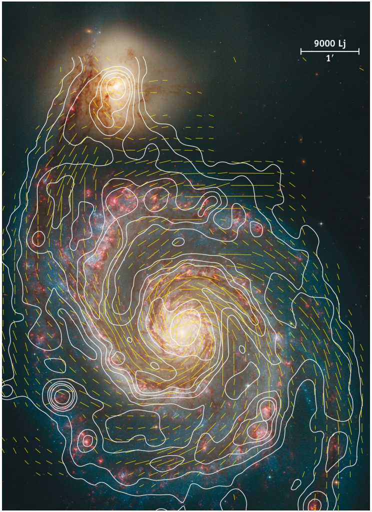
Guicking et al. (2010)

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

Synchrotron radiation



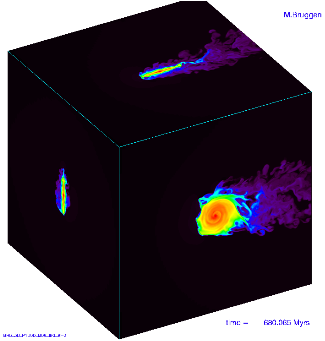
Polarized synchrotron emission in a field spiral: M51



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

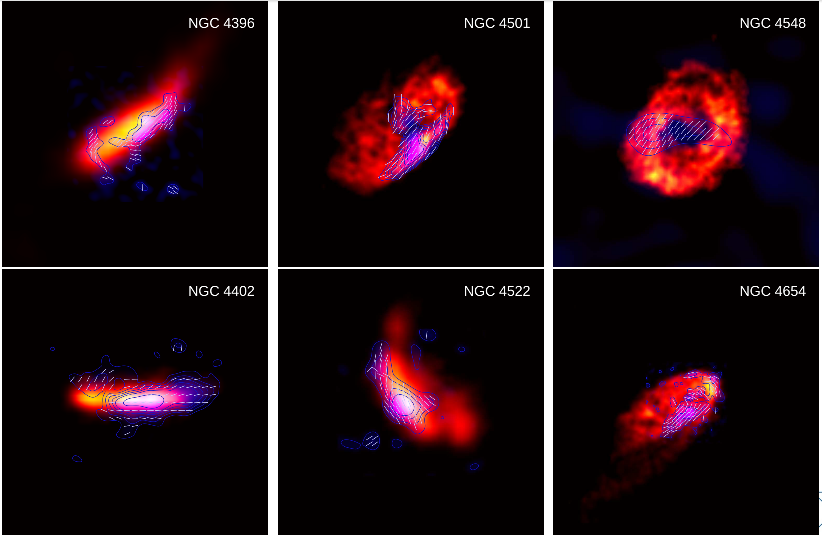


Brueggen (2008)

- 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

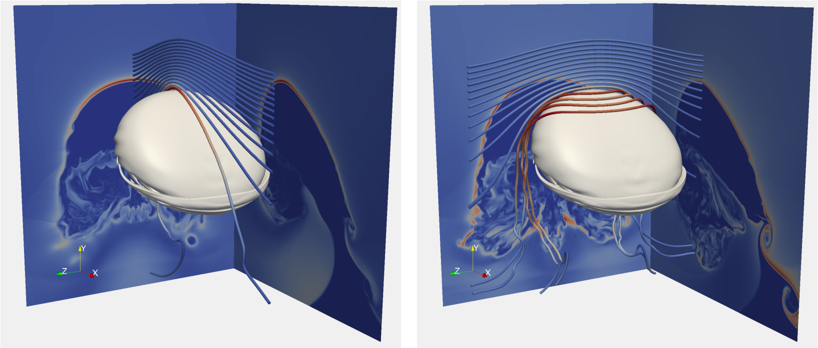
→ resulting radio emission should be unpolarized

Polarized synchrotron ridges in Virgo spirals



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

Magnetic draping around a spiral galaxy

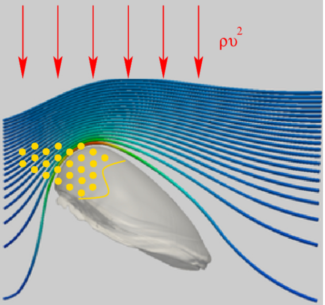


Athena simulations of spiral galaxies interacting with a uniform cluster magnetic field. There is a sheath of strong field draped around the leading edge (shown in red).

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

HITS

Magnetic draping around a spiral galaxy – physics

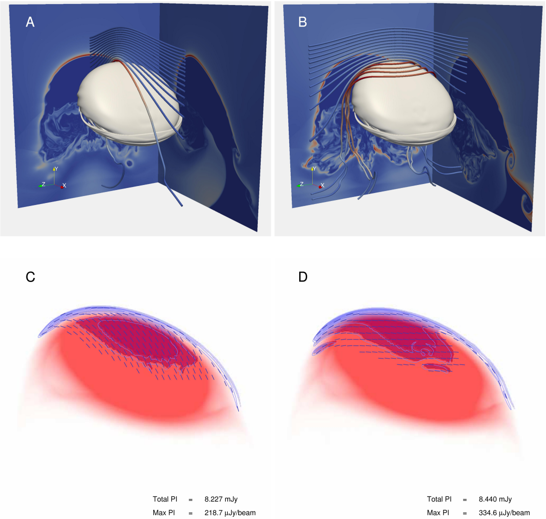


- the galactic gas is pushed back by the ram pressure wind $\sim \rho v^2$
- the stars are largely unaffected and lead the gas
- the draping sheath is formed at the contact of galaxy/cluster wind
- as stars die, their supernova remnants accelerate CRes that populate the draped field lines

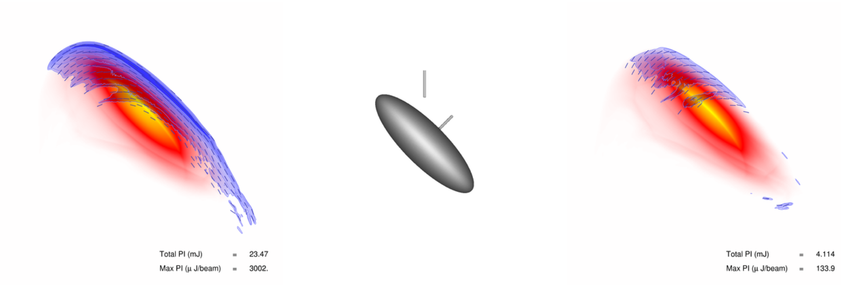
- CRes are transported diffusively (along field lines) and advectively as field lines slip over the galaxy
- CRes emit radio synchrotron radiation in the draped region, tracing out the field lines there $\rightarrow$ coherent polarized emission at the galaxies' leading edges

Magnetic draping and polarized synchrotron emission

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

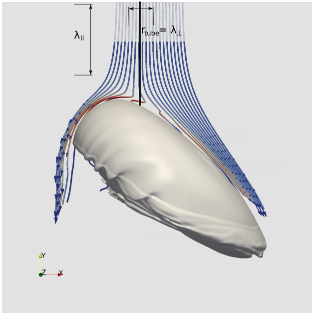


Simulated polarized synchrotron emission



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

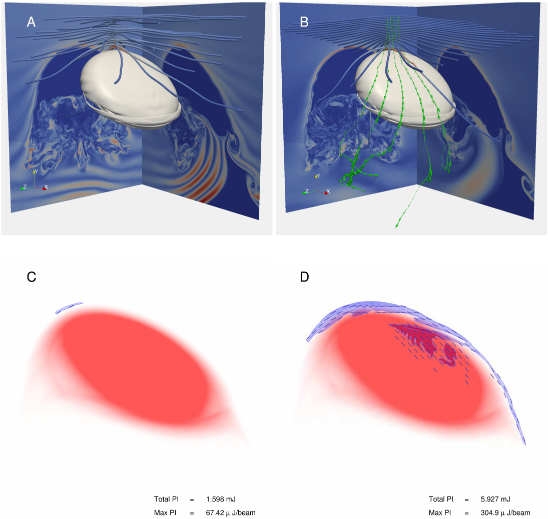
Streamlines in the rest frame of the galaxy



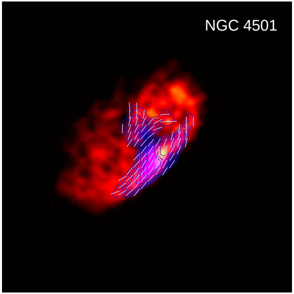
- as the flow approaches the galaxy it decelerates and gets deflected
- only those streamlines initially in a narrow tube of radius $\lambda_\perp \simeq R/\sqrt{3\beta\mathcal{M}^2} \simeq R/15 \simeq 1.3$ kpc from the stagnation line become part of the magnetic draping layer (color coded) $\rightarrow$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

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



Magnetic coherence scale estimate by radio ridges



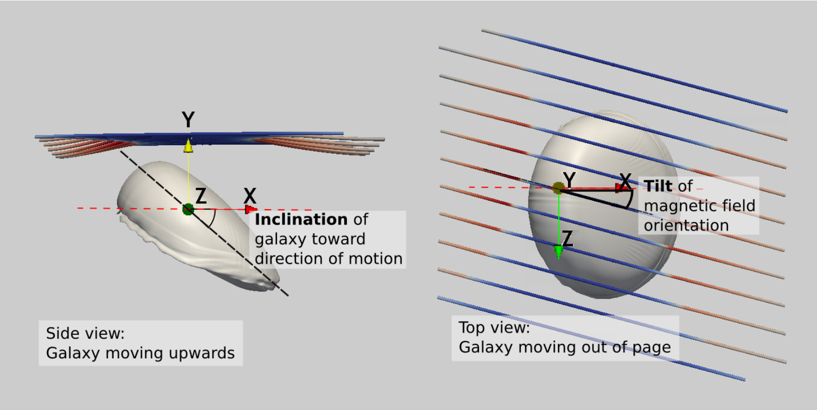
- observed polarised draping emission $\rightarrow$ field coherence length λ_B is at least galaxy-sized
- if $\lambda_B \sim 2R_{\rm gal}$, then the change of orientation of field vectors imprint as a change of the polarisation vectors along the vertical direction of the ridge showing a 'polarisation-twist'

- 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

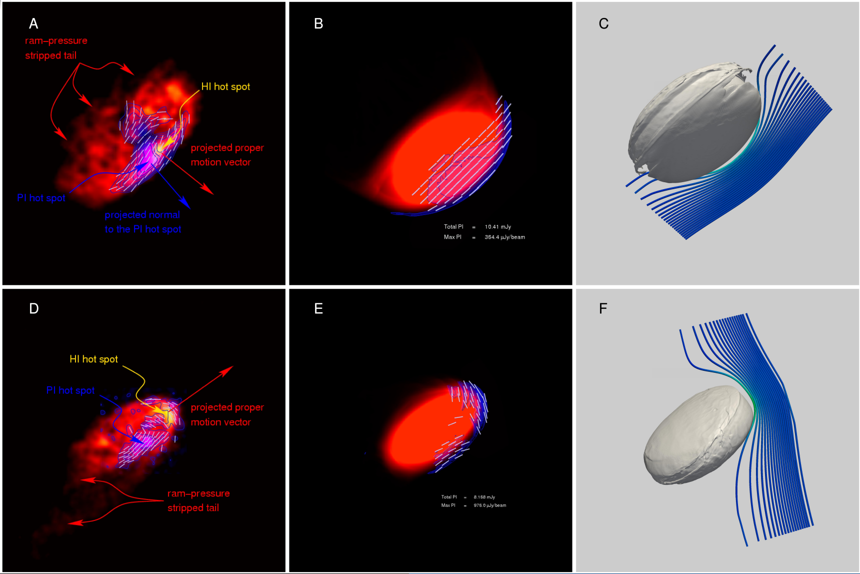
$$L_{\rm coh} \simeq \eta L_{\rm drape} v_{\rm gal}/v_{\rm drape} = \eta \tau_{\rm syn} v_{\rm gal} > 100\,{\rm kpc},$$

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

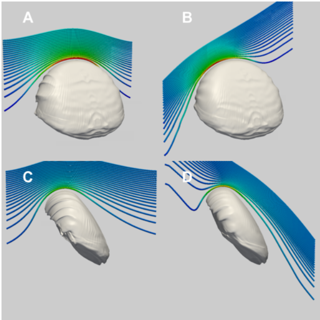


Observations versus simulations



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 $\boldsymbol{B} \parallel \boldsymbol{v}_\mathrm{gal}$

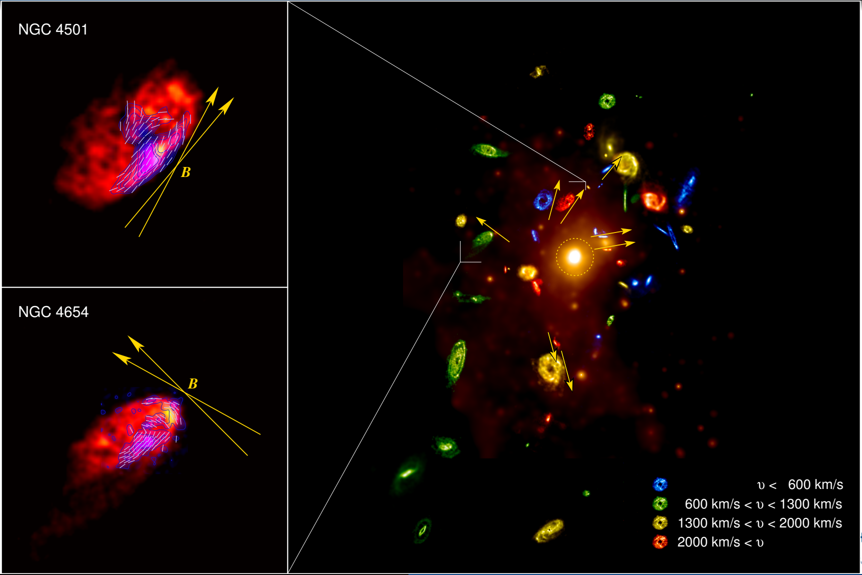


- *geometric bias:* polarized synchrotron emission only sensitive to traverse magnetic field B_t ($\perp$ to LOS) $\rightarrow$ maximum polarised intensity may bias the location of $B_\mathrm{max,\ drape}$ towards the location in the drape with large B_t

Outline

1. Astrophysical concepts
   - Galaxy clusters
   - Shock waves
   - Magnetic fields
2. Magnetic draping
   - Solar system
   - Spiral galaxies
   - Radio emission
3. Implications
   - Magnetic field orientations
   - Kinetic plasma instabilities
   - Evolution of galaxy clusters

Mapping out the magnetic field in Virgo



Magneto-thermal instability: the idea

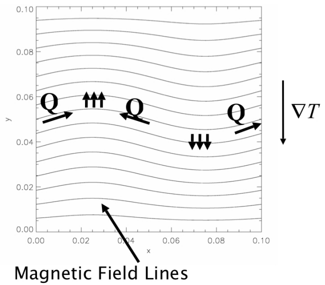


Figure from I. Parrish

Convective stability in a gravitational field:

- Classical Schwarzschild criterion: $\frac{dS}{dz} > 0$
- 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

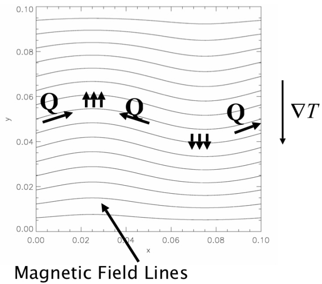


Figure from I. Parrish

Convective stability in a gravitational field:

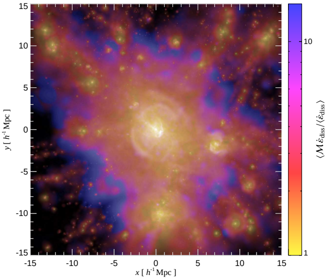
- Classical Schwarzschild criterion: $\frac{dS}{dz} > 0$
- long MFP, Balbus criterion: $\frac{dT}{dz} > 0$
- new instability causes field lines to reorient radially $\rightarrow$ efficient thermal conduction radially

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

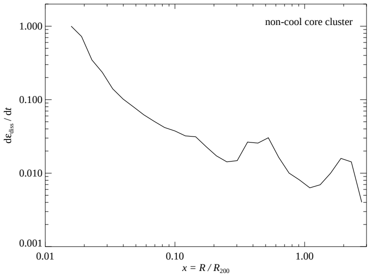
- Adiabatic boundary conditions for $T(r)$: the instability can exhaust the source of free energy $\rightarrow$ isothermal profile
- Fixed boundary conditions for $T(r)$: field lines stay preferentially radially aligned (35 deg mean deviation from radial)

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

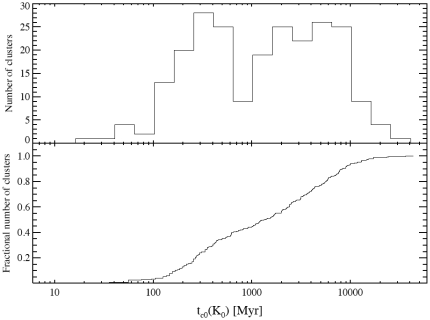


shock strengths weighted by dissipated energy



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

Implications for galaxy clusters (probing cosmology)



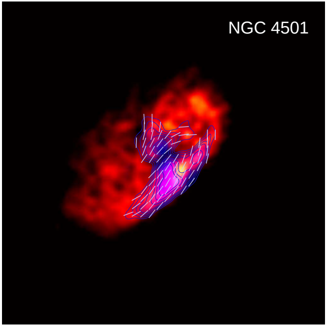
Cavagnolo et al. (2009)

- *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

Speculation: evolutionary sequence of galaxy clusters

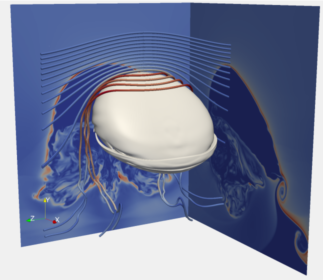
- After a merging event of a non-cool core cluster, the injected turbulence decays on an eddy turnover time $\tau_{\mathrm{eddy}} \simeq L_{\mathrm{eddy}}/\upsilon_{\mathrm{turb}} \sim 300\,\mathrm{kpc}/(300\,\mathrm{km/s}) \sim 1$ Gyr.
- The magneto-thermal instability grows on a similar timescale of 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 self-regularized heating by a super-massive black hole to be stabilized.

Conclusions on magnetic draping around galaxies



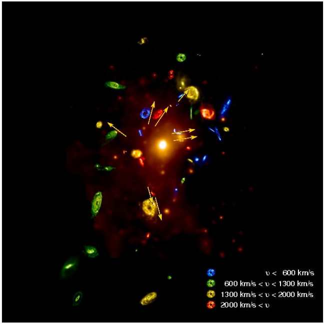
- draping of cluster magnetic fields naturally explains polarization ridges at Virgo spirals

Conclusions on magnetic draping around galaxies



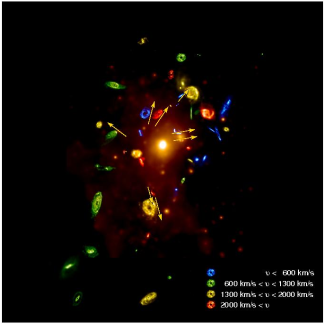
- draping of cluster magnetic fields naturally explains polarization ridges at Virgo spirals
- this represents a new tool for measuring the in situ orientation of cluster magnetic fields

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 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 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

Literature for the talk

- Pfrommer & Dursi, 2010, Nature Phys., 6, 520, *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*