X-shape magnetic fields in galactic halos

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Cosmic rays and their interstellar medium environment
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Outline

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Observational tools

- Linear polarization of starlight & dust thermal emission
  Due to *dust grains* → general ISM
  ☞ $\vec{B}_{\perp}$ (orientation only)

- Zeeman splitting
  Molecular & atomic *spectral lines* → neutral regions
  ☞ $B_{\parallel}$ (strength & sign)

- Faraday rotation
  Caused by *free electrons* → ionized regions
  ☞ $B_{\parallel}$ (strength & sign)

- Synchrotron emission
  Produced by *CR electrons* → general ISM
  ☞ $\vec{B}_{\perp}$ (strength & orientation)

The Milky Way

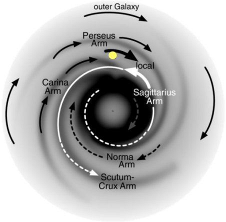
Magnetic field strength

- In general ISM
  - Near the Sun : $B_{\rm ord} \sim 3\ \mu{\rm G}$ & $B_{\rm tot} \sim 5\ \mu{\rm G}$
  - Global spatial distribution : $L_{\rm B} \sim 12$ kpc & $H_{\rm B} \sim 4.5$ kpc
- In ionized regions
  - Near the Sun : $B_{\rm reg} \simeq 1.5\ \mu{\rm G}$ & $B_{\rm fluct} \sim 5\ \mu{\rm G}$
- In neutral regions
  - In atomic clouds : $B \sim$ a few $\mu{\rm G}$
  - In molecular clouds : $B \sim (10 - 3000)\ \mu{\rm G}$

The Milky Way

Magnetic field direction

- Near the Sun
  - $\vec{B}_{\rm reg}$ is horizontal & nearly azimuthal $(p \simeq -7^\circ, -8^\circ)$
- In the Galactic disk
  - $\vec{B}_{\rm reg}$ is horizontal & mostly azimuthal
  - $\vec{B}_{\rm reg}$ reverses direction with decreasing radius
  - $\vec{B}_{\rm reg}$ is symmetric in z
  - $\vec{B}_{\rm reg}$ is neither pure ASS nor pure BSS
- In the Galactic halo
  - $\vec{B}_{\rm reg}$ has horizontal & vertical components
  - $\vec{B}_{\rm reg}$ is anti-symmetric in z



van Eck et al. (2011)

External spiral galaxies

- In galactic disks

  - $B_{\rm ord} \sim (1-5)\ \mu$G & $B_{\rm tot} \sim (5-20)\ \mu$G

  - $\vec{B}_{\rm ord}$ is horizontal & has a spiral stucture

- In galactic halos

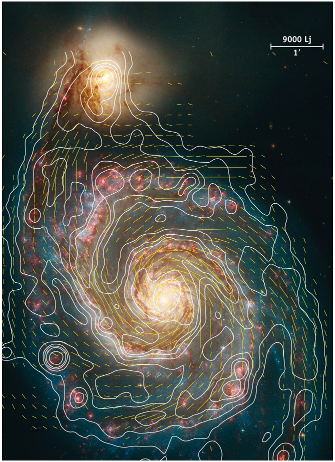
  - $B_{\rm tot} \lesssim 10\ \mu$G

  - $\vec{B}_{\rm ord}$ is X-shaped

Face-on spiral galaxy: M 51

Total intensity contours
+ apparent $\vec{B}$ vectors
at λ 6 cm (5.0 GHz)
(100 m Effelsberg + VLA)

Optical image
(HST)

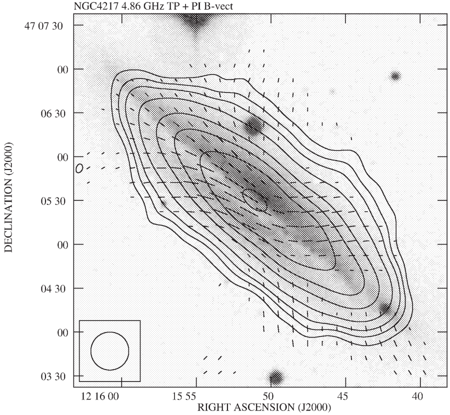


Fletcher et al. (2009)

NGC 4217

Total intensity contours
+ apparent $\vec{B}$ vectors
at λ 6.2 cm (4.86 GHz)
(VLA)

Optical image
(DSS)

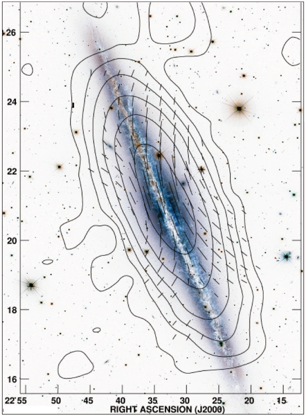


Soida (2004)

NGC 891

Total intensity contours
+ apparent $\vec{B}$ vectors
at λ 3.6 cm (8.35 GHz)
(100 m Effelsberg)

Optical image
(CFHT)



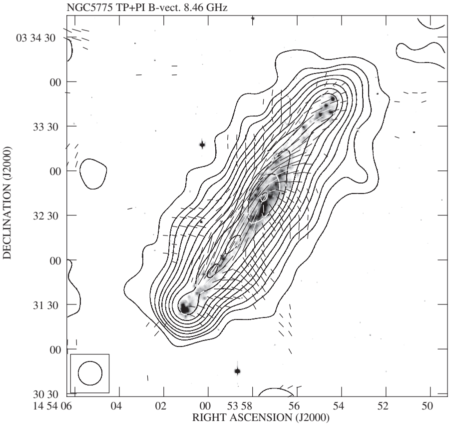
Krause (2009). © MPIfR Bonn & CFHT/Coelum

NGC 5775

Total intensity contours
+ apparent $\vec{B}$ vectors
at λ 3.5 cm (8.46 GHz)
(VLA + 100 m Effelsberg)

Hα image
(VLT)

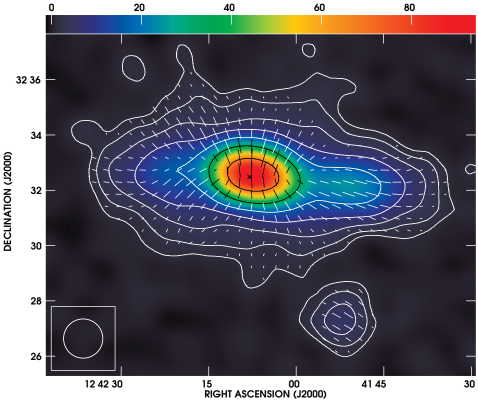
Tüllmann et al. (2000)



Soida et al. (2011)

NGC 4631

Total intensity contours
+ apparent $\vec{B}$ vectors
at λ 3.6 cm (8.35 GHz)
(100 m Effelsberg)

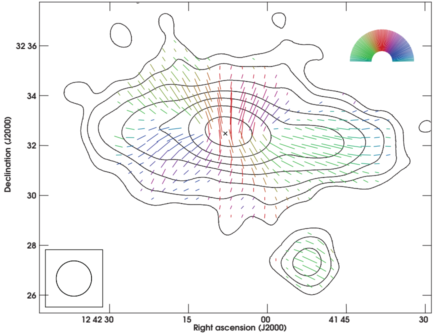


Mora & Krause (2013)

NGC 4631

Total intensity contours
at λ 3.6 cm (8.35 GHz)
(100 m Effelsberg)

+ intrinsic $\vec{B}$ vectors
from λ 3.6 cm & λ 6.2 cm
(VLA + 100 m Effelsberg)



Mora & Krause (2013)

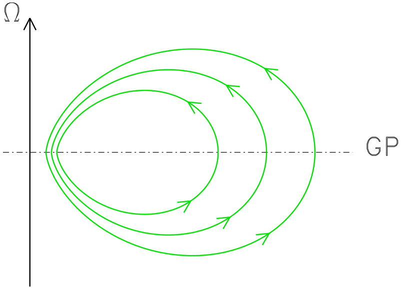
Outline

Possible scenarios

- Large-scale regular magnetic field
  - ★ *Conventional dynamo* in the halo
  - ★ *Dynamo* in the halo + *large-scale wind* from the disk
    or *outflow* from the central region
  - ★ *Dynamo* in the disk + *large-scale wind* from the disk
    or *outflow* from the central region
- Small-scale anisotropic random magnetic field
  - ★ *Spiky wind* ☞ extremely elongated magnetic loops

Conventional dynamo in the halo

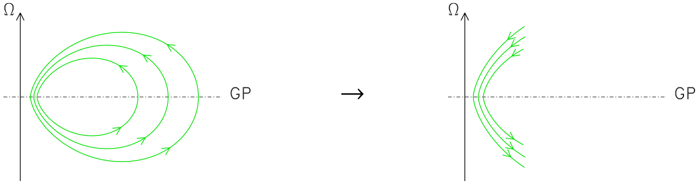
- Dipole-like magnetic field sheared out in the azimuthal direction



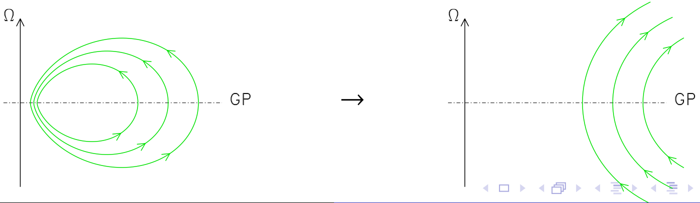
- Very different from an X-shape magnetic field

Halo dynamo + wind

- Oblique wind from the disk

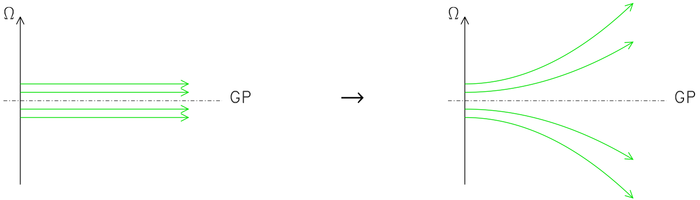


- Champagne flow from the central region



Disk dynamo + wind

- Oblique wind from the disk

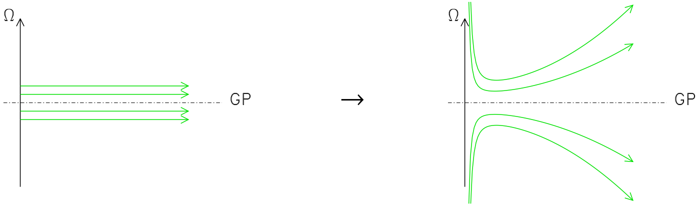


☞ Unphysical, because all field lines converge to the rotation axis
Mathematically, $B_r \to \infty$

☞ Must prevent field lines from reaching the rotation axis

Disk dynamo + wind

- Oblique wind from the disk + bipolar jet from the galactic center



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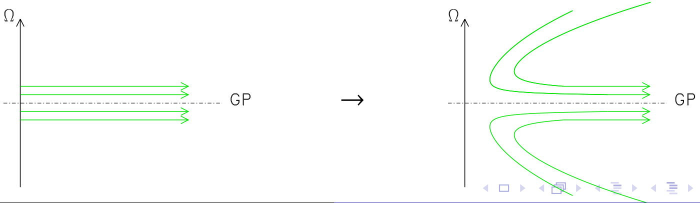
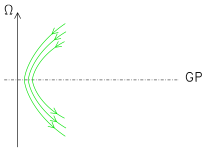
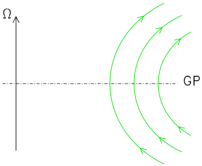


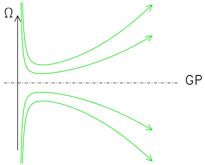
Vertical symmetry

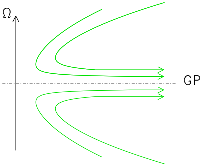
- Halo dynamo + wind
  - ☞ $\vec{B}$ is necessarily anti-symmetric in z





- Disk dynamo + wind
  - ☞ $\vec{B}$ is more likely symmetric in z (but could also be anti-symmetric)





Outline

How to model X-shape magnetic fields ?

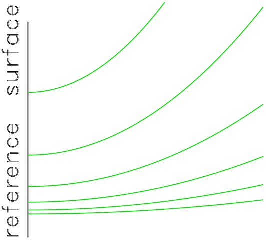
- **Input**

  Consider a magnetic configuration

  defined by a *network of field lines*

  ☞ - shape of field lines

  - distribution of B_n on a reference surface



- **Purpose**

  Derive an analytical expression

  for the associated $\vec{B}(r, \varphi, z)$

- **Method**

  Use the Euler potentials, α and β,

  defined such that $\vec{B} = \vec{\nabla}\alpha \times \vec{\nabla}\beta$

Euler potentials

- **Definition**

  2 scalar functions, α and β, such that $\boxed{\vec{B} = \vec{\nabla}\alpha \times \vec{\nabla}\beta}$

- **Advantages**
  - ⋆ $\vec{B}$ is automatically *divergence-free*

    $$\vec{\nabla} \cdot \vec{B} = 0$$

  - ⋆ α and β are *constant along field lines*

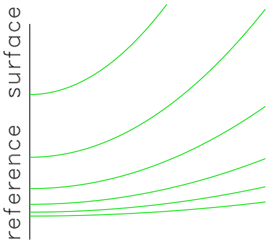
    $$\vec{B} \perp \vec{\nabla}\alpha \perp \text{surfaces of } c^{st}\ \alpha \quad \Rightarrow \quad \vec{B}\ \text{tg}\ \text{surfaces of } c^{st}\ \alpha$$
    $$\vec{B} \perp \vec{\nabla}\beta \perp \text{surfaces of } c^{st}\ \beta \quad \Rightarrow \quad \vec{B}\ \text{tg}\ \text{surfaces of } c^{st}\ \beta$$

  - ⋆ Direct measure of *magnetic flux*

    $$\vec{B} \cdot d\vec{S} = d\alpha\, d\beta$$

How to use the Euler potentials ?

- Consider a *network of field lines*
  - ☞ - shape of field lines
  - - distribution of B_n on a reference surface



- Find 2 independent functions, α and β,

  with - α and β constant along field lines

  - $d\alpha\ d\beta = B_n\ dS$ on the reference surface

- Derive $\vec{\boldsymbol{B}}(r, \varphi, z)$ using $\vec{\boldsymbol{B}} = \vec{\nabla}\alpha \times \vec{\nabla}\beta$

Poloidal, X-shape magnetic field

- **Poloidal magnetic field**

  φ is c^{st} along field lines

  $\Rightarrow$ Take $\beta = \varphi$

- **X-shape magnetic field**

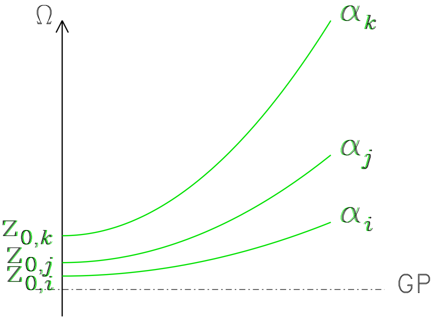
  E.g., $z = z_0\,(1 + a\,r^2)$

  $\Rightarrow z_0 = \dfrac{z}{1 + a\,r^2}$ is c^{st} along field lines

  $\Rightarrow$ Take $\alpha = \mathrm{fc}(z_0)$

- **Exponential decrease with z**

  Take $\alpha = \alpha_0 \exp\left(-\frac{|z_0|}{H}\right)$



Spiral, X-shape magnetic field

- Spiral magnetic field

  E.g., $\varphi = \varphi_0 + f_\varphi(r, z)$

  $\Rightarrow\ \varphi_0 = \varphi - f_\varphi(r, z)$ is cst along field lines

  $\Rightarrow$ Take $\beta = \varphi_0$

- X-shape magnetic field

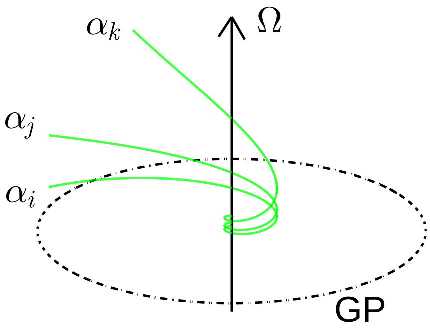
  E.g., $z = z_0\ (1 + a\, r^2)$

  $\Rightarrow\ z_0 = \dfrac{z}{1 + a\, r^2}$ is cst along field lines

  $\Rightarrow$ Take $\alpha = \mathrm{fc}(z_0)$

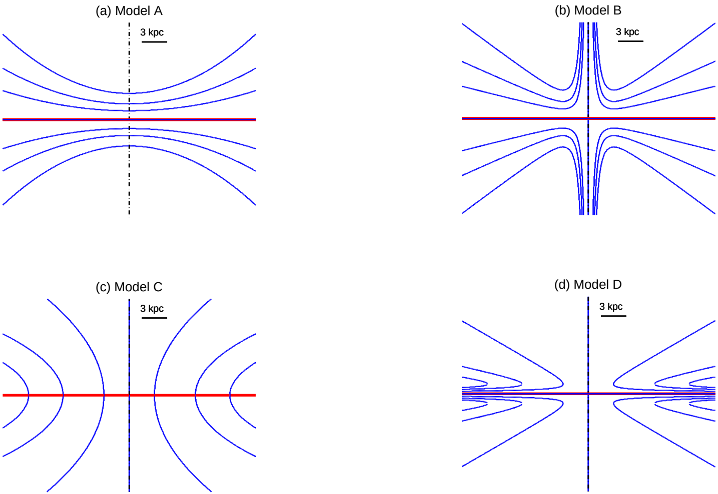
- Exponential decrease with z

  Take $\alpha \;=\; \alpha_0\ \exp\left(-\frac{|z_0|}{H}\right)$

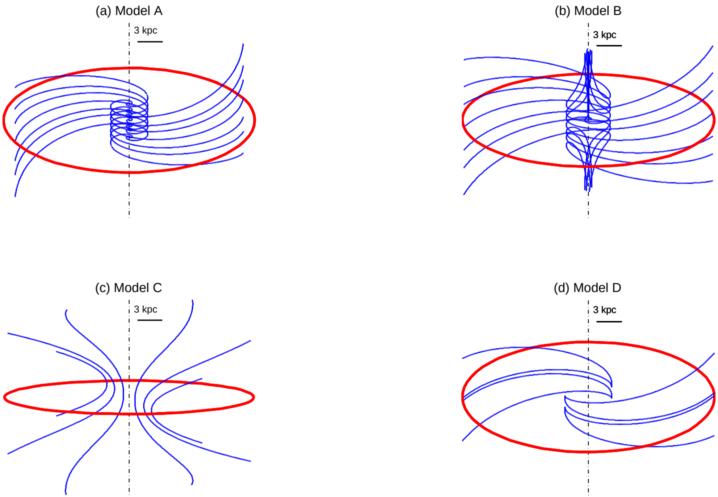


Outline

Poloidal field lines

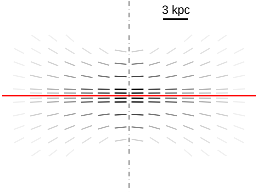


Full, spiraling field lines

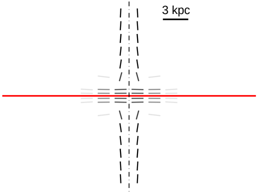


Synchrotron maps

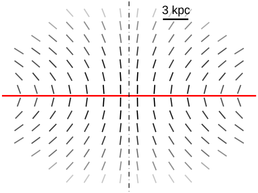
(a) Model A



(b) Model B



(c) Model C



(d) Model D