Galactic winds and the symmetry properties of galactic magnetic fields

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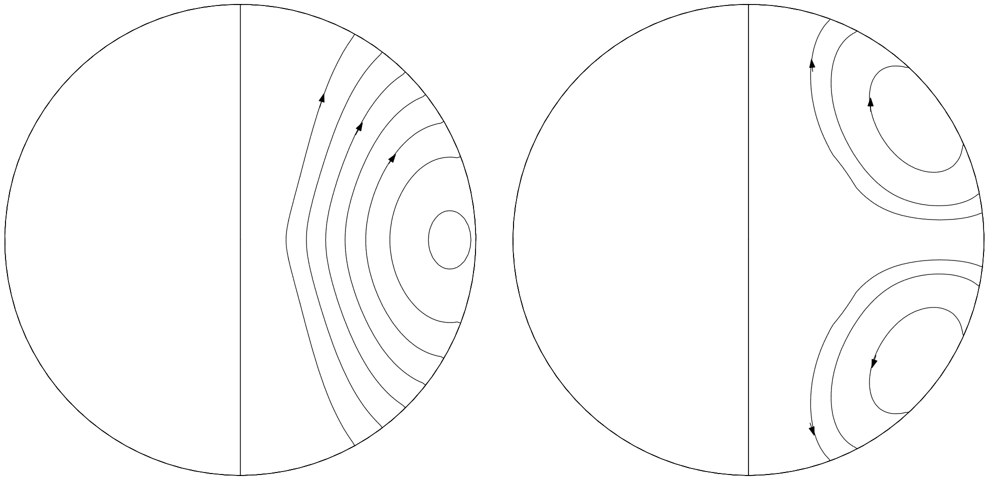
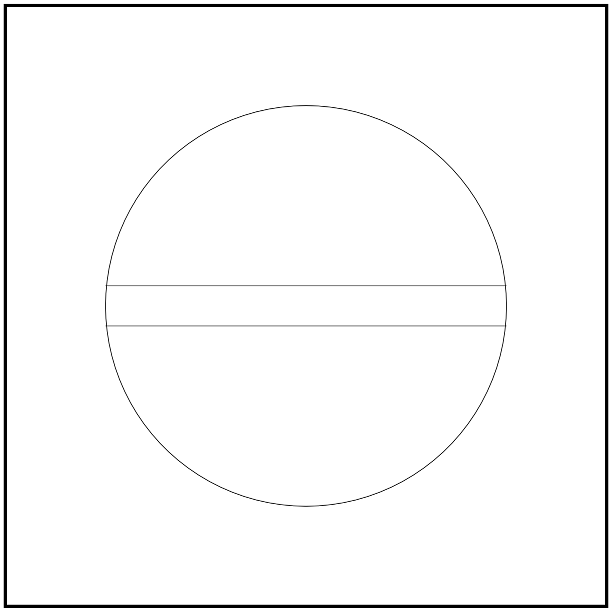


NAIVE EXPECTATIONS FROM DYNAMO THEORY

- Simple dynamos in spheres tend to excite odd parity (dipole-like) magnetic fields (near marginal excitation, at least).
- Dynamos in flattened systems, as used for galactic studies, excite even parity (quadrupole-like) fields)



ARE GALAXIES MAGNETICALLY JUST FLATTENED DISKS?

FLAT DISC (maybe flared) + QUASI-SPHERICAL HALO

BOTH ROTATE, AND HAVE TURBULENT MOTIONS PRESENT

→ BOTH ARE PLAUSIBLE SITES FOR DYNAMO ACTION
Sokoloff & Shukurov (Nature, 1990)

BUT, are the two hemispheres of the halo really so well connected magnetically?

QUESTION: IF DISC DOES WANT TO PRODUCE A QUADRUPOLE-LIKE FIELD, AND THE HALO A DIPOLE-LIKE FIELD, HOW DO THEY INTERACT?

IS THERE COMPETITION OR COEXISTENCE? (peaceful??!)

DOES IT MATTER?!

– OR JUST OF INTEREST TO DYNAMO PEOPLE??

WHAT DO THE OBSERVATIONS TELL US?

THE MILKY WAY

- Sun et al. (2008): Milky Way halo contains a large-scale magnetic field of dipole-like parity.
- Disc field appears to be of quadrupole-like parity.
- *Prima facie* this agrees with the suggestion of Sokoloff & Shukurov (1990)
- How robust is the halo result?

EXTERNAL GALAXIES

- Need nearly edge-on galaxies. Difficult to determine disc and halo parities (faint polarized radio emission in halo, lack of polarized background sources).
- Heesen et al. (2009a,b): radio continuum polarimetry of nearby edge-on galaxy NGC 253. Observe axisymmetric toroidal component in disc, together with a poloidal halo component. "X-shaped" poloidal field in halo.
- Disc field is quadrupole-like (even parity).
- Halo field is probably quadrupole-like, but "odd parity field cannot be excluded because Faraday data for halo are not conclusive".
- Other galaxies: no conclusions re halo parity yet possible.

GALACTIC WINDS – important ingredient?

- Evidence that Milky Way has strong galactic wind, of a few hundred km/s.
- NGC 253 has wind with cosmic ray bulk speed ~ 300 km/s.
- Other galaxies?
- Suggests that wind should be included in relevant dynamo models.

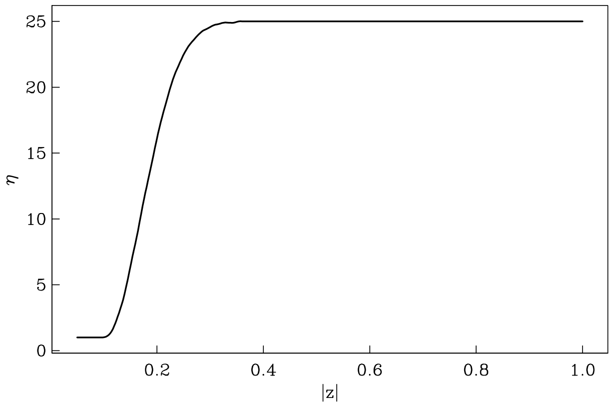


Figure 1: Dependence of η on $|z|$ for $\eta_{\rm R} = 25$.

THE DYNAMO MODEL

- Use $\pm$ standard mean field dynamo model for a generic disc galaxy:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B} + \alpha \mathbf{B} - \eta \nabla \times \mathbf{B})$$

- $\mathbf{u} = \Omega \times \mathbf{r} + \mathbf{U}_{\rm W}$; $\mathbf{U}_{\rm W}$ is the galactic wind.
- Ω is given by a Brandt law, with z-dependence in halo.
- Turbulent diffusivity increases strongly from disc to halo. Usually asymptotic ratio $\eta_{\rm R} = 25$, sometimes $\eta_{\rm R} = 5$ for comparison with previous work.
  Disc value is $\eta_{\rm d}$, used for all scalings.
- Alpha effects in disc and halo regimes are independent, so define coefficients

  $R_{\alpha,{\rm disc}} = \alpha_{0,{\rm disc}} R/\eta_d$, $R_{\alpha,{\rm halo}} = \alpha_{0,{\rm halo}} R/\eta_d$.
  (so $R_{\alpha,{\rm halo}}(\textbf{effective}) \sim R_{\alpha,{\rm halo}}/\eta_{\rm R}$)
- Wind is vertical in region $z \le z_d$, becoming radial in $z \ge 2z_d$, and increasing with $|z|$ from 0 to U_0. Define $C_{\rm wind} = U_0 R/\eta_d$.
- Integrate dynamo equations in a sphere radius R.
- Nominal disc thickness is $z_d = 0.1R$.

PROCEDURE

Fix rotation, $R_{\alpha,\mathrm{disc}}$.

Treat $R_{\alpha,\mathrm{halo}}$, C_{wind} as free parameters.

Integrate equations step by step until regular behaviour found (steady or oscillatory). Uniform grid in r and θ, usually 101×201 mesh points.

Monitor P_{d}, P_{h}, parities of disc and halo regions.

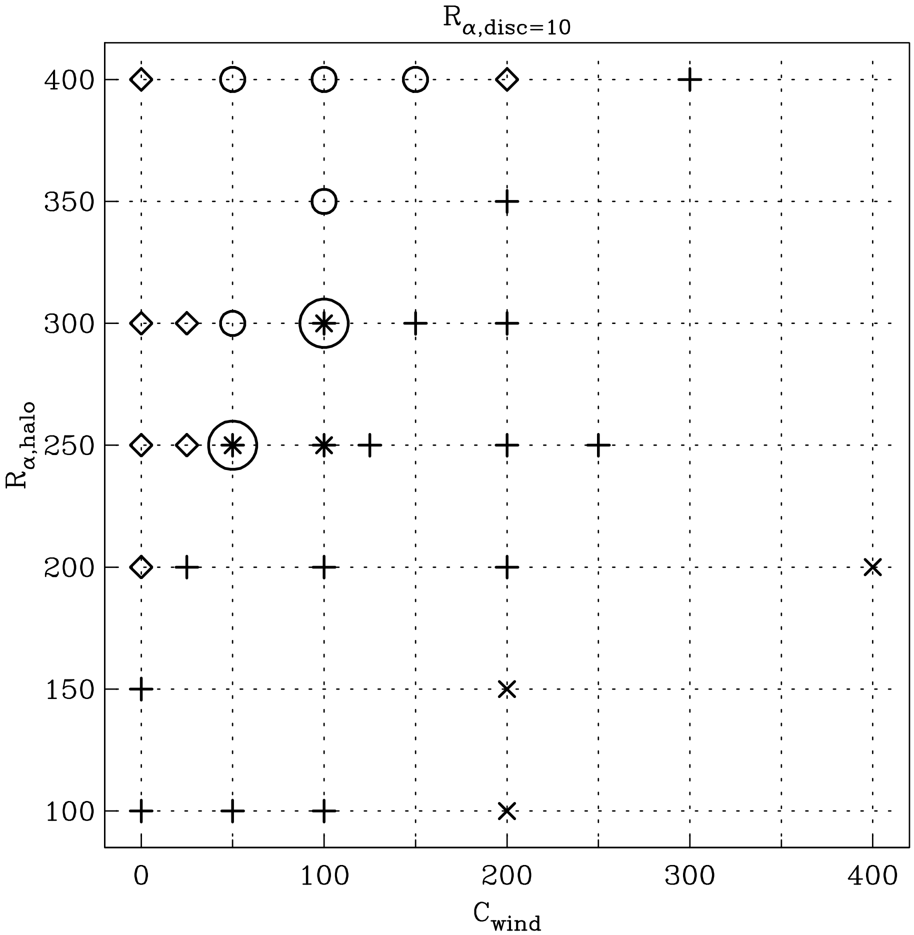
Find steady or oscillatory solutions.

May have $P_{\mathrm{d}} = P_{\mathrm{h}} = +1$, i.e. disc enslaves halo;

or $P_{\mathrm{d}} = P_{\mathrm{h}} = -1$, halo enslaves disc;

or $P_{\mathrm{d}} \approx +1$, $P_{\mathrm{h}} \approx -1$ (quasi-independent behaviour);

or something else.



SYNOPTIC DIAGRAM

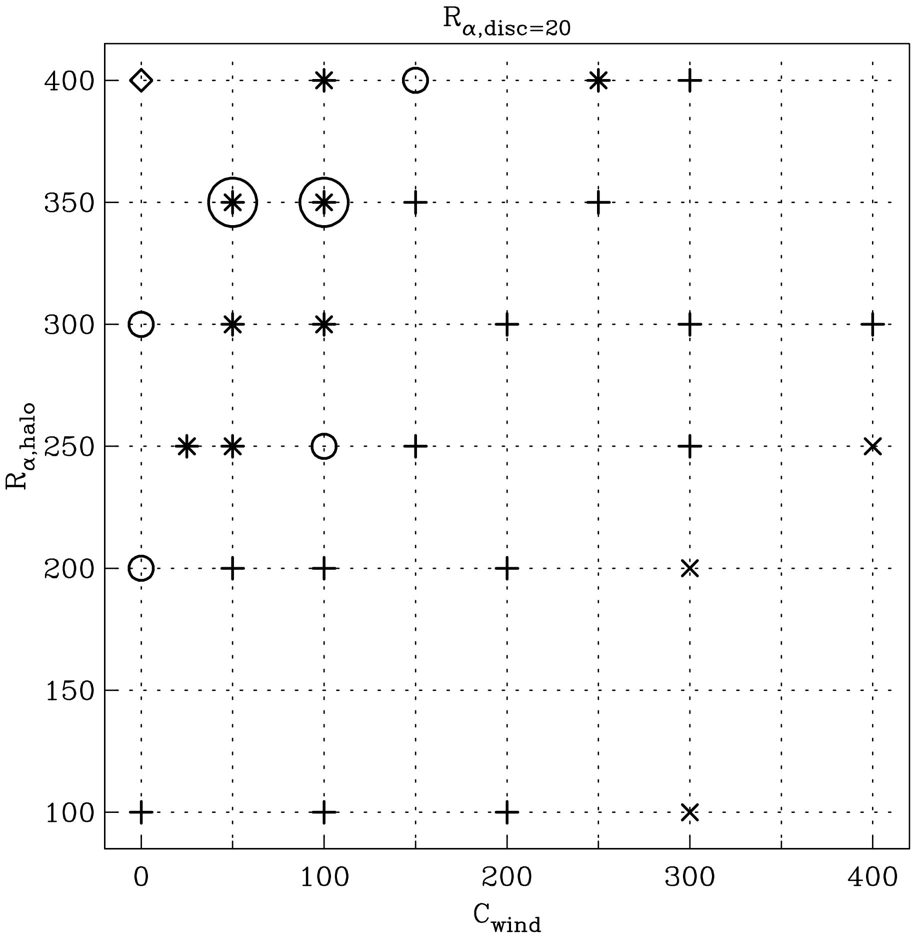
$R_{\alpha,\text{disc}} = 10$, $\eta_\text{R} = 25$.

Key:

$*$: $P_\text{disc} \approx +1, P_\text{halo} \approx -1$
$+$: $P_\text{disc}, P_\text{halo} \approx +1$
$\Diamond$: $P_\text{disc}, P_\text{halo} \approx -1$
$\otimes$: oscillatory, sometimes near $P_\text{disc} \approx +1, P_\text{halo} \approx -1$
$\times$: decaying solution, dynamo not excited

SYNOPTIC DIAGRAM

$R_{\alpha,\mathrm{disc}} = 20$, $\eta_{\mathrm{R}} = 25$.



Key:

$*$: $P_{\mathrm{disc}} \approx +1, P_{\mathrm{halo}} \approx -1$
$+$: $P_{\mathrm{disc}}, P_{\mathrm{halo}} \approx +1$
$\lozenge$: $P_{\mathrm{disc}}, P_{\mathrm{halo}} \approx -1$
$\bigcirc$: intermediate/other type of solution
$\otimes$: oscillatory, sometimes near $P_{\mathrm{disc}} \approx +1, P_{\mathrm{halo}} \approx -1$
$\times$: decaying solution, dynamo not excited

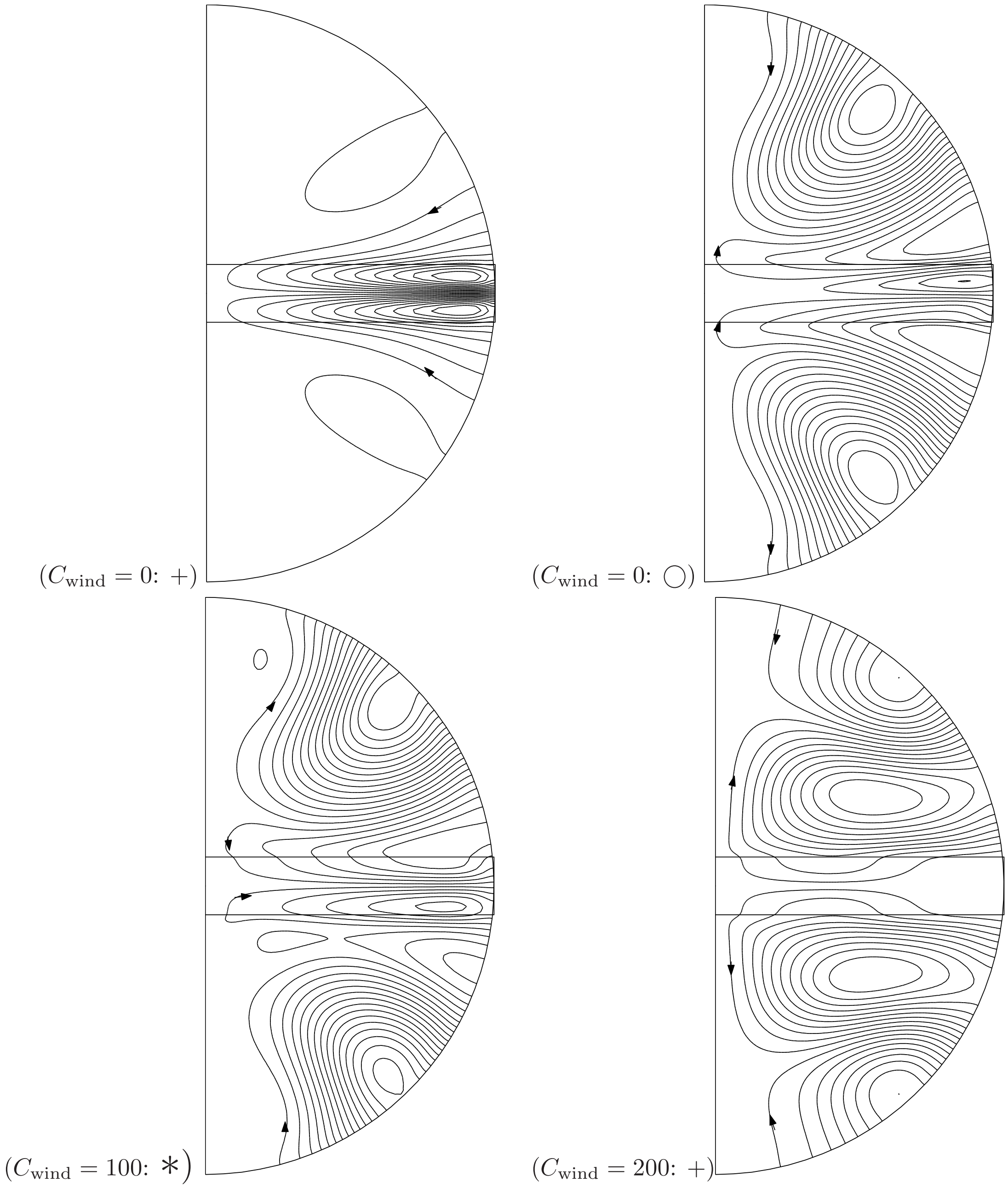


Figure 1: Top left panel has $R_{\alpha,\rm halo} = 100$, in the other panels $R_{\alpha,\rm halo} = 300$.

NOTE

- "Natural" quadrupole-like nature of galactic fields can be perturbed by presence of halo dynamo, especially with strong diffusivity contrast.
- Halo poloidal fields naturally quite X-like if of dipole-like parity. This can be enhanced by a wind.
- Solutions with $P_{\rm d} \approx +1$, $P_{\rm h} \approx -1$ were **not** found with $\eta_{\rm R} = 5$: large diffusivity contrast is needed for such behaviour.
- For, e.g., $R_{\alpha,\rm halo} = 300$, as $C_{\rm wind}$ increases, first a state with a X-like halo field, with $P_{\rm h} \approx -1$, $P_{\rm d} \approx 1$ is reached.
  Then a wholly quadrupole-like state is found for larger wind speeds, as the disc and halo become more strongly linked, and the disc enslaves the halo.
- Eventually, for large enough wind speeds, the dynamo is not excited.
- $C_{\rm wind} = 100$ corresponds to $U_0 = 1.5$km/s for $\eta_{\rm d} = 10^{26}{\rm cm}^2{\rm s}^{-1}$. Observed speeds of 150+ km/s apply to only a small part of the multiphase ISM. They correspond to some sort of mean field averaging over the various components.
- Speeds of a few km/s are consistent with other estimates of outflows consistent with efficient dynamo action (e.g. Sur et al.)
- Presence of wind (or other outflow) consistent with/necessary for current ideas about dynamos.
- Multiple metastable solutions may co-exist for some parameters.

CONCLUSIONS

- Outflows are an essential ingredient for the dynamo.
- Winds can lift significant toroidal field into the halo.
- Wind + strong diffusivity contrast *can* give even/odd parity fields in disc/halo respectively – but situation is complex, and many behaviours are possible.
- More and better observations are needed to clarify what needs to be understood/explained. → LOFAR, SKA, ...?
- For example, how does the presence of X-shaped halo fields correlate with wind speed?
  What is the range of field topologies in spiral galaxies?
- What *is* the halo diffusivity? It'd be nice (but difficult ...) to have a good observational estimate.
- At the moment, models can "explain" ± anything!

("Galactic winds and the symmetry properties of galactic magnetic fields", Moss, D., Sokoloff, D., Beck, R., Krause, M., 2010, A&A 512, A61)