Small-Scale Dynamo in Supernova-Driven Interstellar Turbulence

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Galactic dynamo - large and small scale

gas density

temperature

(Gent, Shukurov, Sarson, Fletcher & Mantere 2013)

(Gressel et al. 2008, Gressel & Elstner 2020)

(Korpi et al. 1999, Hanasz et al. 2009, Wang & Abel 2009, Rieder & Teyssier 2016, Rieder & Teyssier 2017*a*, Rieder & Teyssier 2017*b*, Pakmor et al. 2017, Steinwandel et al. 2019) show no LSD or LSD without SSD.

Large scale dynamo

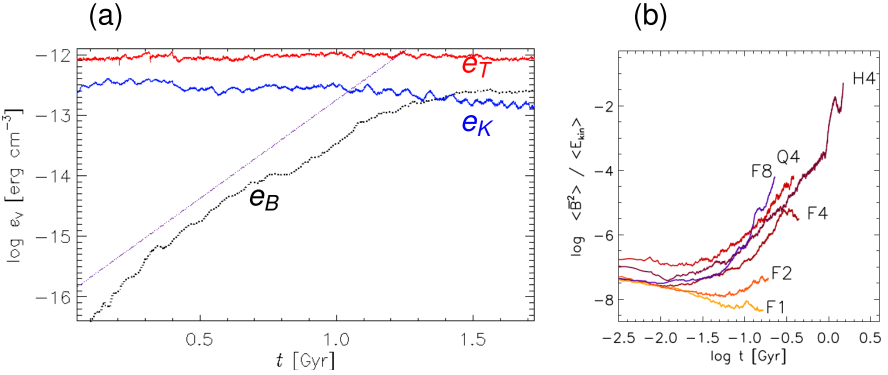


Figure: (a) Magnetic energy evolution (Gent, Shukurov, Sarson, Fletcher & Mantere 2013) rotation 2x $\sigma_{\rm sn}$ (also 1x $\sigma_{\rm sn}$), (b) (Gressel 2008) 1 – 8x $\sigma_{\rm sn}$.

Large scale vs turbulent field

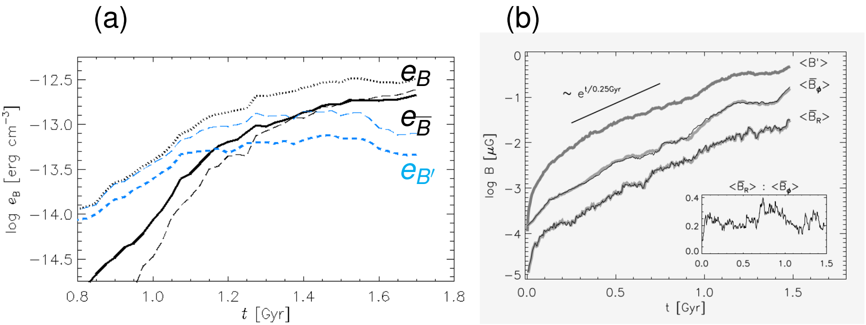


Figure: (a) Magnetic energy of mean and fluctuating field evolution (Gent, Shukurov, Sarson, Fletcher & Mantere 2013) Gaussian smoothing (thick) vs horizontal averaging (thin), (b) (Gressel 2008) horizontal averaging. Is there a small scale dynamo or just tangling of the large scale field?

Distinguishing tangling from small scale dynamo

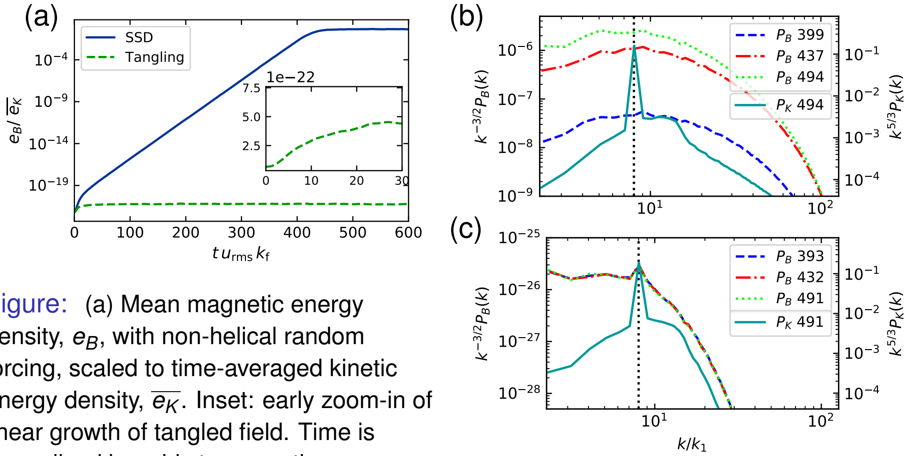


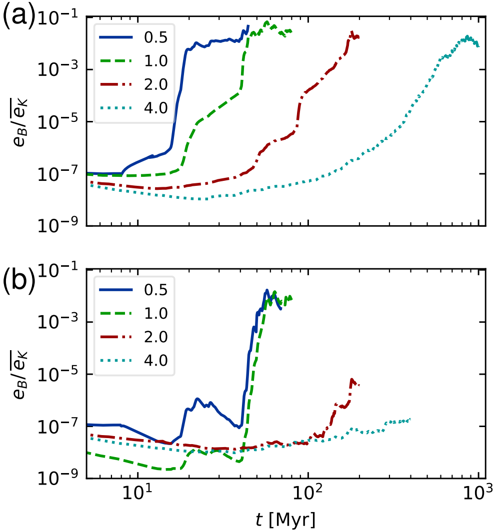
Figure: (a) Mean magnetic energy density, e_B, with non-helical random forcing, scaled to time-averaged kinetic energy density, $\overline{e_K}$. Inset: early zoom-in of linear growth of tangled field. Time is normalised by eddy turnover time, $1/k_{\rm f}u_{\rm rms}$. (b) SSD and (c) tangling compensated power spectra, at times given in the legends.

Figure: Note that the kinetic energy uses the right-hand axes. Forcing scale, $k_{\rm f}/k_1 = 8$: vertical dotted line.

Experimental setup

- 3D periodic ISM 1 ppcc 256(200) pc on each side
- SN rate comparable to solar neighbourhood 0.2 – 8 $\dot{\sigma}_{\rm sn}$
- Energy: radiative cooling and UV-heating, hyperdiffusion and shock diffusion
- Induction: hyperdiffusion and $\eta \in [0, 0.05]$ kpc km s^{-1}
- Momentum: hyperdiffusion and shock diffusion $\nu = 0$
- Continuity: shock diffusion
- Resolution 0.5, 1, 2 and 4 pc

Magnetic energy growth rates



Magnetic energy density for resolutions $\delta x = 0.5$–$4\ \mathrm{pc}$, scaled to time-averaged kinetic energy density $\overline{e_K}$ for resistivity (a) $\eta = 10^{-4}$ & (b) $10^{-3}\,\mathrm{kpc\,km\,s^{-1}}$.

Dependence on Mach number (Haugen, Brandenburg & Mee 2004)

Magnetic energy growth rates

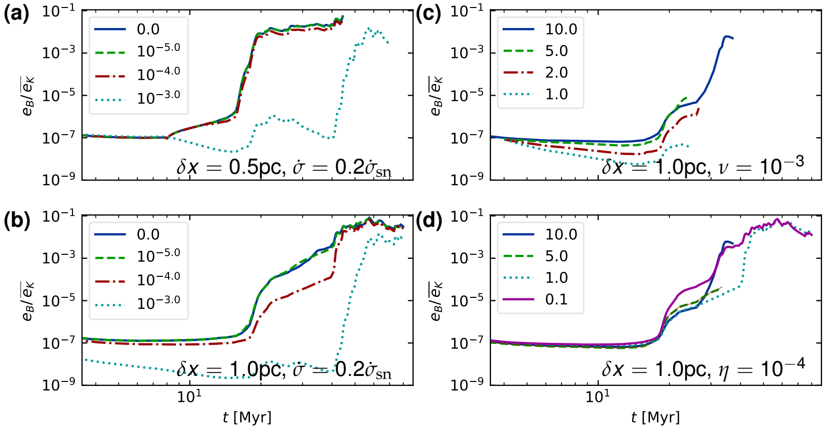


Figure: Magnetic energy density e_B normalized by the time-averaged kinetic energy $\overline{e_K}$ for various resistivities η for values given in each panel of resolution δx and SN rate $\dot\sigma$ normalized by the solar neighborhood rate $\dot\sigma_{\rm sn} \simeq 50\,{\rm kpc}^{-3}\,{\rm Myr}^{-1}$. $\nu = 0$, except where Pm is varied with ν fixed (c) or η fixed (d). Dependence on Pm (Haugen, Brandenburg & Dobler 2004)

Magnetic energy growth rates

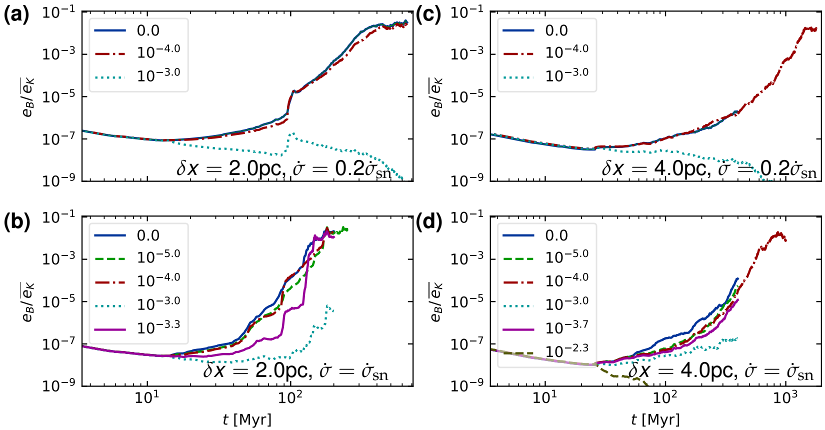


Figure: Magnetic energy density e_B normalized by the time-averaged kinetic energy $\overline{e_K}$ for various resistivities η for values given in each panel of resolution δx and SN rate $\dot\sigma$ normalized by the solar neighborhood rate $\dot\sigma_{\rm sn} \simeq 50\,\text{kpc}^{-3}\,\text{Myr}^{-1}$. $\nu = 0$ η fixed (d).

Energy spectra during kinematic dynamo

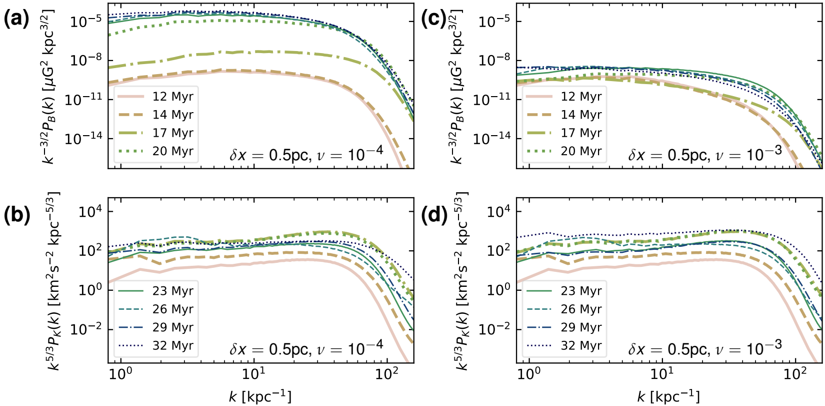


Figure: Compensated magnetic (a, c) and kinetic (b, d) power spectra for $\delta x = 0.5$ pc at times given in megayears by the legends. Resistivity is $\eta = 10^{-4}$ (a, b) or $\eta = 10^{-3}$ (c, d). Compensation is by the Kazantsev spectrum $k^{3/2}$ (a, c) or the Kolmogorov spectrum $k^{-5/3}$ (b, d).

Energy spectra by resolution and resistivity

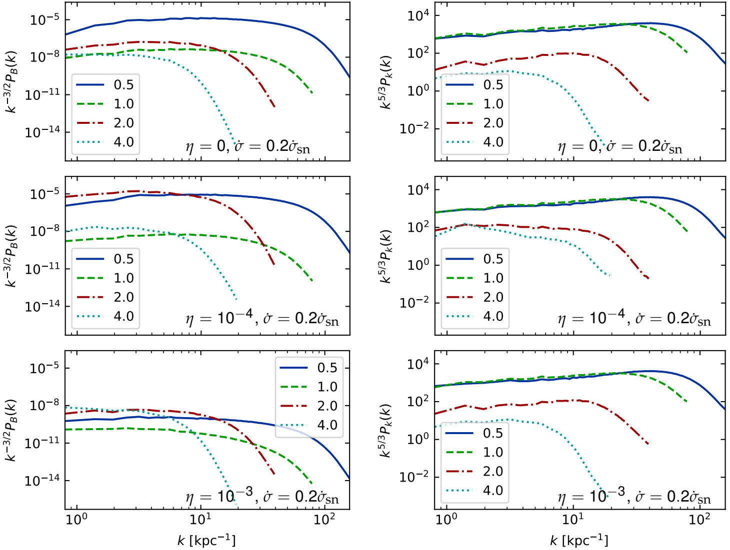


Figure: Compensated power spectra magnetic (left) and kinetic (right). Resistivity η & supernova rate $\dot\sigma$, 19.5 Myr ($\delta x = 0.5$, 1 pc), 100 Myr (2, 4 pc).

Energy spectra by SN rate

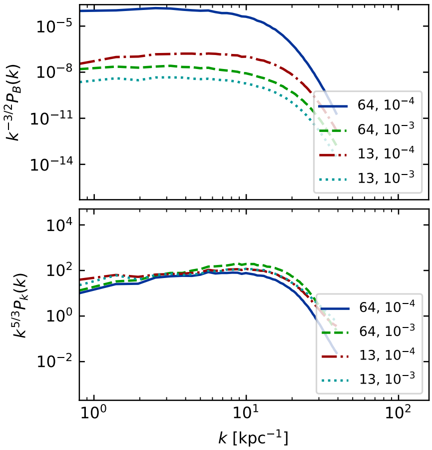


Figure: Compensated power spectra magnetic (upper) and kinetic (lower). Resistivity η & supernova rate $\dot{\sigma}$, $140\,\mathrm{Myr}$ ($\delta x = 2\ \mathrm{pc}$).

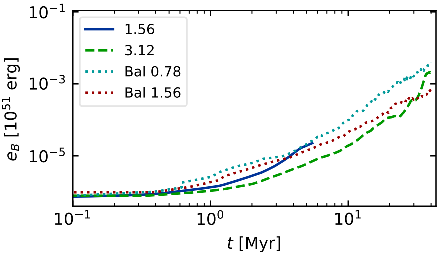


Figure: Magnetic energy density with a weak imposed field and $\dot{\sigma} = 8\dot{\sigma}_{\mathrm{sn}}$ matching (Balsara et al. 2004).

Summary of results

- SN turbulence convergent for $\delta x \lesssim 1\,\mathrm{pc}$
- SSD is very easily excited in the ISM - contrast isothermal high (Haugen, Brandenburg & Mee 2004)
- (Balsara et al. 2004) experiment confirmed as SSD and not tangling
- Critical dynamo number and growth rates not clearly Pm dependent in multi-phase ISM contrast isothermal SSD (Haugen, Brandenburg & Dobler 2004) – (Käpylä et al. 2018) baroclinic effects vs (Federrath et al. 2011)
- For $\dot{\sigma} \in (0.2\dot{\sigma}_{\mathrm{sn}}, 8\dot{\sigma}_{\mathrm{sn}})$ SSD critical dynamo number increases with $\dot{\sigma}_{\mathrm{sn}}$
- SSD saturates at $\sim 5\%$ energy equipartion independent of Rm or δx

... Summary of results

- (Gent, Shukurov, Fletcher, Sarson & Mantere 2013):
  - $\eta \simeq 8 \cdot 10^{-4}\,\mathrm{kpc\,km\,s^{-1}}$, $\delta x = 4\,\mathrm{pc}$, SSD
  - LSD with galactic angular momentum $\Omega = \Omega_{\mathrm{sn}}$

  $\Omega_{\mathrm{sn}} = 25\,\mathrm{km\,s^{-1}\,kpc^{-1}}$ is the rate in the solar neighbourhood
- (Gressel et al. 2008) & (Gressel & Elstner 2020):
  - $\eta \simeq 6.5 \cdot 10^{-3}\,\mathrm{kpc\,km\,s^{-1}}$, δx is 8.3 and 6.7 pc, no SSD
  - LSD with $\Omega \geq 4\Omega_{\mathrm{sn}}$
- Rm at the largest scales would be 7.5 times higher in (Gent, Shukurov, Fletcher, Sarson & Mantere 2013) sufficient to explain LSD at $\Omega = \Omega_{\mathrm{sn}}$
- low resolution (Korpi et al. 1999) $\Omega = \Omega_{\mathrm{sn}}$: no SSD nor LSD
- SSD critical $\eta > 10^{-3}\,\mathrm{kpc\,km\,s^{-1}}$ for $\delta x \leq 1\,\mathrm{pc}$ (Fig. 5b,c) and what $\dot{\sigma}_{\mathrm{sn}}$?

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acknowledgements

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Software: Pencil Code

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Growth in warm/hot gas

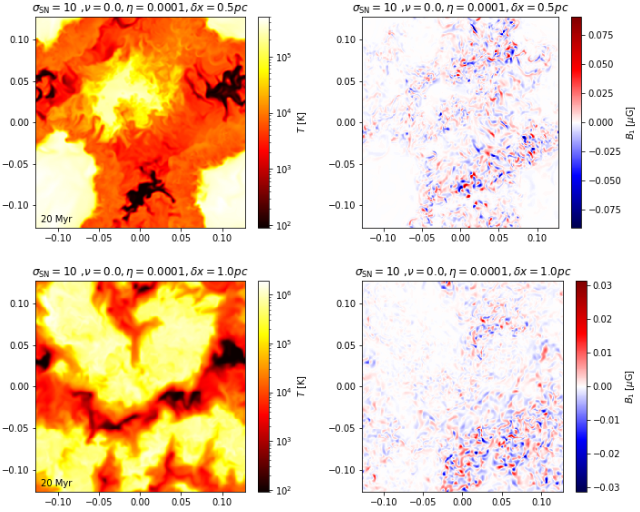

Figure: Slices for resolution of 0.5 pc and 1 pc sampled from the kinematic dynamo state.

No correlation