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Growth rate of magnetic field during starburst phase in a galaxy

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Abstract. During an active star formation phase, it is conceivable that the turbulent level of a galaxy increases and consequently an increase in magnetic field by turbulent dynamo process. We point out that the thickness of the dynamo region is sensitive to the turbulent level. We examine the linear growth rate of three different dynamos, namely, $\alpha\omega$, $\alpha^2\omega$ and α^2 dynamos. We find that the dependence of the growth rate on turbulent level is quite different for different dynamos. Moreover, the growth rate is not necessary monotonic to turbulence level even in the linear regime.

Keywords. ISM: magnetic fields, galaxies: starburst, turbulence

1. Introduction and model

Interstellar medium (ISM) in spiral galaxies is highly inhomogeneous and is in vigorous turbulent motion. They are mostly ionized and is a highly conducting fluid. Due to the differential rotation of the galaxy, ISM suffer large scale shear as well. These are essential ingredients of a turbulence dynamo, which can amplify a weak seed magnetic field into a large scale strong field. Star formation activity, in particular massive star formation, is the major (if not the only) driving force of ISM turbulence. Supernovae, stellar winds from massive stars, and alike churn the ISM and drive the turbulence. It is conceivable that star formation activity can occur in bursts or periodically. When the activity is high, the galactic dynamo may be turned on and the galactic magnetic field strength increases. When the activity is low, the dynamo becomes dormant and the magnetic field decays. Here we emphasize that the thickness of the galactic disk is sensitive to turbulence, and is a crucial factor in the dynamo process (e.g., Ko & Parker 1989, Ko 1990, Ko 1993). This is often overlooked but it may be the determining factor on the growth rate of the magnetic field.

Let us consider a simple kinematic dynamo with time dependent coefficients. To illustrate ideas, we take the simplest geometry: slab geometry. A region of the ISM disk (away from the galactic centre) is described in Cartesian coordinates where x is radial, y is azimuthal and z is perpendicular to the disk. All quantities depend on t and z only. As we expect the thickness of the disk may expand and contract in the course of time, it is convenient to introduce the comoving coordinate $\xi = z/h(t)$, where $h(t)$ is the characteristic scale height of the disk. The density of the disk satisfies $\rho = \bar{\rho}(\xi)/h(t)$, and velocity $u_z = \xi \mathrm{d}h/\mathrm{d}t$. The kinematic dynamo equation becomes,

$$\frac{\partial A}{\partial t} - \frac{\eta}{h^2}\frac{\partial^2 A}{\partial \xi^2} - \frac{\alpha B_*}{h} = 0\,, \tag{1.1}$$

$$\frac{\partial B_*}{\partial t} - \frac{1}{h^2}\frac{\partial}{\partial \xi}\left(\eta \frac{\partial B_*}{\partial \xi}\right) + G\frac{\partial A}{\partial \xi} + \frac{1}{h}\frac{\partial}{\partial \xi}\left(\alpha \frac{\partial A}{\partial \xi}\right) = 0\,, \tag{1.2}$$

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where

$$A = A_y\,, \quad B_x = -\frac{\partial A}{\partial z}\,, \quad B_y = \frac{B_*}{h}\,, \quad B_z = 0\,, \quad G = \frac{\partial u_y}{\partial x}\,, \tag{1.3}$$

α is the mean helicity of the turbulent velocity field, G is the shear.

2. Examples and discussion

To educate ourselves, we consider some simple examples. First if α, G, η are independent of ξ, we can make the following simplification to Equations (1.1) & (1.2),

$$\{A(t,\xi), B_*(t,\xi)\} = \{\tilde{A}(t), \tilde{B}_*(t)\} \exp\left[-i\,q\xi - \int_0^t \frac{\eta q^2}{h^2}\,\mathrm{d}t'\right]\,, \tag{2.1}$$

where $\tilde{A}(t)$ and $\tilde{B}(t)$ satisfy

$$\frac{\mathrm{d}\tilde{A}}{\mathrm{d}t} = \frac{\alpha}{h}\,\tilde{B}_*\,, \quad \frac{\mathrm{d}\tilde{B}_*}{\mathrm{d}t} = \frac{\alpha q^2}{h}\left(1 - i\,\frac{N_G}{N_\alpha}\right)\tilde{A}\,, \quad N_G = \frac{Gh^2}{\eta q^2}\,, \quad N_\alpha = \frac{\alpha h}{\eta q}\,. \tag{2.2}$$

We call N_G the shear dynamo number and N_α the turbulent dynamo number. If N_G/N_α is constant (i.e., $\alpha \propto Gh$), analytic solution exists and the amplitude of the dynamo wave is governed by

$$\{A, B_*\} \propto \exp\left[\int_0^t \frac{\eta q^2}{h^2}\left(\sqrt{\frac{N_\alpha^2 + \sqrt{N_\alpha^4 + N_\alpha^2 N_G^2}}{2}} - 1\right)\mathrm{d}t'\right]\,. \tag{2.3}$$

Suppose a spiral galaxy undergoes a rapid starburst, and the turbulence level changes from v_0 to v almost instantaneously, and so do α, G, η and h because they depend on the turbulence level v. Let $\alpha = \alpha_0 \tilde{v}^a$, $G = G_0 \tilde{v}^b$, $\eta = \eta_0 \tilde{v}^c$, $h = h_0 \tilde{v}^d$, and $\tilde{v} = v/v_0$. Consider the galactic dynamo is in dormant state before the starburst, i.e., the amplitude of the dynamo wave does not change. In this case, $N_{a0}^2\left(N_{G0}^2 + 4\right) = 4\,$. After the rapid starburst the growth rate of the dynamo is

$$\sigma = \frac{\eta_0 q^2}{h_0^2}\left[\frac{\tilde{v}^{(a-d)}}{\sqrt{N_{G0}^2 + 4}}\sqrt{2 + \sqrt{4 + N_{G0}^2\,(N_{G0}^2 + 4)\,\tilde{v}^{2(b+d-a)}}} - \tilde{v}^{(c-2d)}\right]\,. \tag{2.4}$$

Note that when $N_{G0} = 0$ it is an α^2 dynamo, and if $N_{G0} \gg 1$ it is an $\alpha\omega$ dynamo. The upshot is when the thickness of the dynamo region h increases with the turbulence level $\tilde{v}$, the growth rate does not necessarily increases monotonically with the turbulence level. For example,

(1) $(a, b, c, d) = (1, 0, 1, 1)$: as $\tilde{v}$ increases, σ increases monotonically until a maximum.

(2) $(a, b, c, d) = (0, 0, 1, 2)$: as $\tilde{v}$ increases, σ increases to a maximum and then decreases towards zero.

These examples illustrate the subtlety of how the growth rate of the dynamo dependence on turbulence if the thickness of the dynamo also depends on turbulent level. The message is if one wants to understand the evolution of magnetic field, don't forget to put the thickness of the disk into the dynamics.

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