THE FULL "ALPHA-TENSOR" DUE TO SUPERNOVAE AND SUPERBUBBLES IN THE GALACTIC DISK

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ABSTRACT. We provide a simple and realistic expression for the alpha-tensor in the Galactic disk, when turbulence is driven by supernova explosions and superbubbles.

1. Introduction

Turbulent motions in the Galactic disk play an essential role in the generation of large-scale magnetic fields (Parker 1971). Mathematically, their impact on the mean magnetic field, $< \mathbf{B} >$, is described by the electromotive force, $\mathcal{E}$, which, to the lowest order of approximation, is linearly related to the mean field through the so-called alpha-tensor (Moffatt 1978):

$$\mathcal{E} = \underline{\underline{\alpha}} . < \mathbf{B} > , \tag{1}$$

where

$$\underline{\underline{\alpha}} = \begin{pmatrix} \alpha_R & -V_{esc} & 0 \\ V_{esc} & \alpha_\Phi & 0 \\ 0 & 0 & \alpha_Z \end{pmatrix} \tag{2}$$

in a cylindrical coordinate system with origin at the Galactic center.

A general analytical expression for the alpha-tensor due to a vertical distribution of axisymmetric explosions was derived by Ferrière (1993). In the following we make use of this general expression to interpret the different components of $\underline{\underline{\alpha}}$ physically and to calculate them when turbulence is driven by supernova (SN) explosions and superbubbles (SBs) in the Galactic disk.

2. Physical Interpretation

The four non-vanishing components of $\underline{\underline{\alpha}}$ are plotted in Figure 1 as a function of Galactic height, Z, in the case of spherical explosions occurring at the midplane. All functions are antisymmetric with

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respect to Z and go to zero as Z approaches the maximum radius of influence of an explosion, r_m.

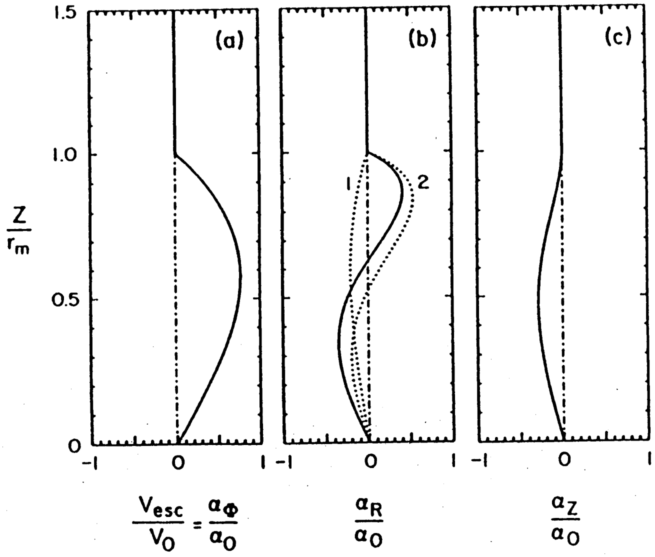

Figure 1. Components of the alpha-tensor vs. Galactic height, when turbulence is driven by spherical explosions occurring at the midplane. V_0 and α_0 are characteristic velocities.

Physically, a given explosion carries field lines away from its center and rotates them in the direction opposite to the effective large-scale rotation (to satisfy conservation of angular momentum). The net effect of an ensemble of explosions taking place at the midplane is to expel magnetic flux away from the midplane and to generate magnetic field in the direction perpendicular to the prevailing field (alpha-effect).

The off-diagonal component of $\underline{\underline{\alpha}}$, V_{esc}, gives the effective vertical velocity at which magnetic flux escapes from the Galactic disk.

The diagonal components of $\underline{\underline{\alpha}}$ give the effective rotational velocity associated with the alpha-effect when the mean magnetic field is radial, azimuthal or vertical. Let us restrict our attention to $Z \geq 0$. When the mean field is azimuthal about the Galactic center, the loops of magnetic flux produced by an explosion rotate about the vertical in the direction opposite to the large-scale rotation rate, Ω (Figure 2), so that their normal acquires a positive component along the mean field direction. This gives rise to a positive α_Φ (Figure 1a).

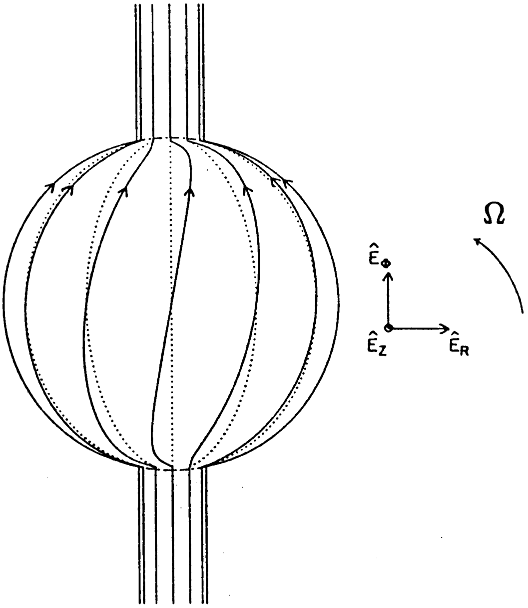

Figure 2. View from above the Galactic plane of the field lines swept up by a spherical explosion (dotted line) and twisted by the large-scale rotation (solid line) when the mean magnetic field is azimuthal about the Galactic center.

When the mean magnetic field is radial, not only do field lines rotate at a rate Ω about the Galactic center, but they are also sheared at a rate G by the large-scale differential rotation. The resulting effective rotation rate is $\Omega + G$, which, contrary to Ω, is negative. Therefore, counterrotation with respect to $\Omega + G$ leads to a negative α_R (dotted line 1 in Figure 1b). Furthermore, because the ambient magnetic field is continuously sheared by the differential rotation, it does not exactly coincide with the mean field; its longitudinal component about the mean field direction is negative at the early times following an explosion (i.e., when only low Z are involved) and positive at late times (i.e., when the explosion reaches high Z). The vertical escape of this field component gives rise to a second contribution to α_R, which is negative at low Z and positive at high Z (dotted line 2 in Figure 1b). The total α_R is shown in solid line in Figure 1b.

Finally, when the mean magnetic field is vertical, the loops of magnetic flux formed by an explosion counterrotate with respect to $(\Omega + G\ \cos^2\varphi)$, where φ is the azimuthal angle about a vertical axis through the explosion site (Figure 3). On average over φ, the normal to the loops acquires a negative vertical component, and the resulting α_Z is negative (Figure 1c).

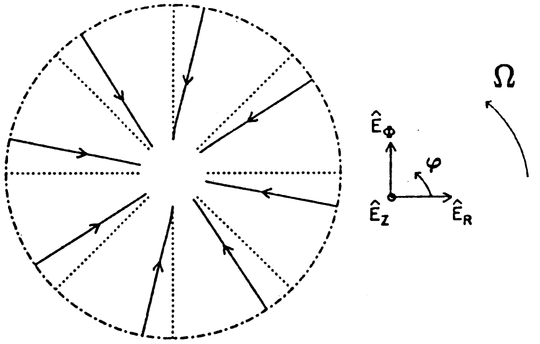

Figure 3. Same as in Figure 2 when the mean magnetic field is vertical.

3. Effects of Supernovae and Superbubbles

A realistic expression for the components of $\underline{\underline{\alpha}}$ in the Galactic disk can be obtained by applying the formal results of Ferrière (1993) to the main sources of explosions in the interstellar medium (ISM), namely SNs and SBs. Here, we make the following assumptions:

- Type I SNs play a negligible role, owing to their low intrinsic frequency and their large scale height (Heiles 1987).
- Type II SNs are equally divided between isolated and clustered events (Stone 1981).
- Isolated SNs are exponentially distributed along the vertical and their remnants are spherical.
- Clustered SNs produce SBs, which are cylindrical (Heiles 1987) and distributed in luminosity according to a power law (Kennicutt et al. 1989).

Under these conditions and when reasonable values are used for the ISM parameters, the escape velocity and the azimuthal and radial α-parameters in the solar neighborhood can be approximated by

$$V_{esc}(Z) = (2.6 \text{ km s}^{-1}) \ Z \left(1 + 0.45 \ Z^2\right)^{-1} , \tag{3}$$

$$\alpha_\Phi(Z) = (0.14 \text{ km s}^{-1}) \ Z \left(1 + 0.125 \ Z^{2.1}\right)^{-1} , \tag{4}$$

and

$$\alpha_R(Z) = -(1.9 \times 10^{-2} \text{ km s}^{-1}) \ Z \left(1 + 0.125 \ Z^{2.1}\right)^{-1} , \tag{5}$$

where Z is in units of 100 pc (Figure 4). Horizontally, these functions follow the distribution of Type II SNs, which peaks in spiral arms and in the ring of molecular clouds.

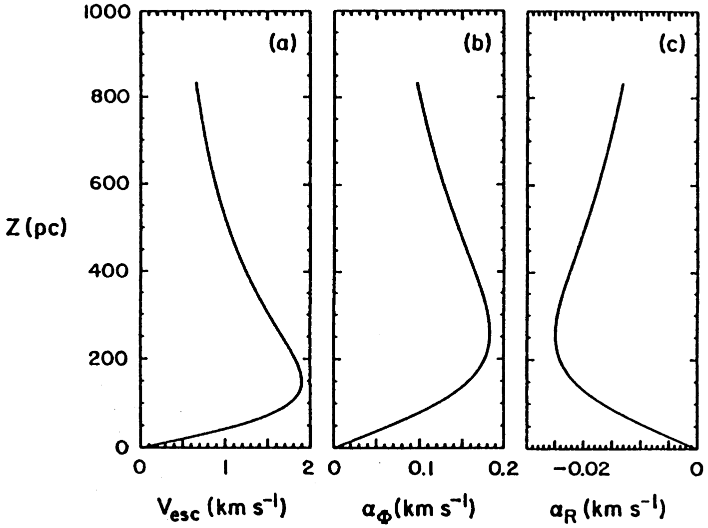

Figure 4. Components of the alpha-tensor due to isolated SNs and SBs together vs. Galactic height.

Near the midplane, SBs are twice more efficient than isolated SNs at removing magnetic flux from the Galactic disk, and seven (six) times more efficient at producing an azimuthal (radial) alpha-effect. Away from the midplane, the role played by SBs becomes comparatively even more important, mainly because they grow much higher than isolated SNs.

References

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