Intense magnetic fields produced by neutrino beams in supernovae

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(Received 23 September 1997)

It is shown that the ponderomotive force of a nonuniform intense neutrino beam can generate large-scale quasistationary magnetic fields in supernovae.
[S1063-651X(98)09702-5]

PACS number(s): 95.30.Qd, 97.30.Qt, 95.30.Cq, 97.60.Bw

It is well known [1] that in supernovae as well as on the surfaces of neutron stars there exist strong magnetic fields whose origin is not understood. It has been suggested that nonstationary magnetic fields could have been created either by a kinematic dynamo or by the baroclinic vector. In the dynamo process we should have a finite plasma flow, whereas the baroclinic vector mechanism requires that the cross product of the electron temperature and density gradients are nonzero. Thus the charge separation caused by the dynamo and baroclinic processes produces an electric field whose curl gives rise to temporally growing magnetic fields. Opher and Wichoski [2] have evaluated various magnetic-field generation processes for astrophysical conditions. However, a recent numerical simulation by Vainshtein *et al.* [3] suggests that a large-scale magnetic field cannot be produced by the nonlinear dynamo process. Thus the latter as well as the baroclinic processes could be ruled out as possible mechanisms for the generation of intense large-scale magnetic fields in supernovae, as the plasma flow and the scale lengths of the density and temperature inhomogeneities are not sufficient to cause a significant effect.

However, the background of most high-energy astrophysical plasmas, such as those in supernovae, star interiors, and neutron stars (pulsars), contains intense fluxes of neutrinos in addition to electrons, positrons, and quarks. Our objective here is to show that the ponderomotive force [4] of a random-phased nonuniform neutrino beam can create intense *stationary* magnetic fields that can account for the observations.

We consider the propagation of an ensemble of random-phased electron neutrino wave packets in an electron plasma with a fixed ion background. The frequency ω_ν and the wave vector $\mathbf{k}_\nu$ of the neutrino oscillations is then [5] $\omega_\nu=[k_\nu^2c^2+m^2c^4/\hbar^2]^{1/2}+\sqrt{2}(G/\hbar)n_e$, where m is the neutrino mass, c the speed of light, G the Fermi constant of the weak interaction, $\hbar$ the Planck constant, and n_e the electron number density. The index of refraction N for the neutrinos is thus $N=k_\nu^2c^2/\omega_\nu^2\approx 1-(\Omega^2/\omega_\nu^2)-2\sqrt{2}Gn_e/\hbar k_\nu c$, where $\Omega=mc^2/\hbar\ll k_\nu c$.

Introducing the neutrino amplitude wave function $\psi_{\mathbf{k}_\nu}$ (not the wave function for a single neutrino) we write the neutrino energy density as $W_{\mathbf{k}_\nu}=\Sigma_{\mathbf{k}_\nu}\langle|\psi_{\mathbf{k}_\nu}|^2\rangle/4\pi$ and the neutrino power density as $P_{\mathbf{k}_\nu}\sim W_{\mathbf{k}_\nu}c$. In a nonlinear dispersive medium, an ensemble of random-phased nonuniform neutrino beams exerts a ponderomotive force [4] $\mathbf{F}=(1/8\pi)\Sigma_{\mathbf{k}_\nu}(N-1)\nabla\langle|\psi_{\mathbf{k}_\nu}|^2\rangle$ on the electrons as well as on the ions. Physically, the presence of a spatially varying neutrino wave function in a dielectric medium induces a dipole moment $\mathbf{d}$, which is the product of the index of refraction and the neutrino amplitude wave function. The ponderomotive force is then simply $\mathbf{d}\cdot\nabla\psi_{\mathbf{k}_\nu}$. In a steady state, the sum of the electron and ion ponderomotive forces is balanced by the $-\langle\mathbf{j}\times\mathbf{B}\rangle/c$ force [6], where the angular brackets denote the ensemble average, $\mathbf{j}$ is the plasma current density, and $\mathbf{B}$ is the magnetic field. The force balance together with Ampere's law yields an estimate for the electron gyrofrequency $\omega_{ce}=eB_\theta/m_ec$, where e is the magnitude of the electron charge, B_θ the azimuthal component of the magnetic field, and m_e the electron mass. Thus [7] $\omega_{ce}\approx\omega_{pe}(\omega_GW_0/\omega_\nu E_p)^{1/2}$ at the beam axis when the intensity distribution is of the form $\Sigma_{\mathbf{k}_\nu}\langle|\psi_{\mathbf{k}_\nu}|^2\rangle=W_0\exp(-r^2/r_0^2)$. Here r_0 is the effective radius [which is of the order of the neutrino trapping scalelength (a few kilometers) within the neutrinosphere] of the neutrino beam, W_0 is the maximum neutrino energy density on the beam axis, $\omega_G=G\langle n_e\rangle/\hbar$, $\omega_{pe}=(4\pi n_0e^2/m_e)^{1/2}$ is the electron plasma frequency, and $E_p=\langle n_e\rangle m_ec^2$ is the plasma energy density. In the derivation of the stationary magnetic field, we have assumed that the $\mathbf{j}\times\mathbf{B}$ force dominates the pressure gradient force, which implies that $\omega_{ce}/\omega_{pe}\gg(v_{te}/c)(L_B/L_{nT})^{1/2}$, where v_{te} is the electron thermal velocity and $L_B(L_{nT})$ the scale length of the magnetic-field (equilibrium density and temperature) gradient.

Let us now estimate the strength of the magnetic fields for a supernova by means of some typical plasma and neutrino field parameters. Accordingly, we take $\langle n_e\rangle\sim10^{30}$ cm^{-3} and a neutrino power density of order 10^{29} W/cm^2. Thus, for 1-MeV neutrinos we find that $\omega_G/\omega_\nu\sim10^{-13}$, where we have used $G=10^{-37}$ eV cm^3. The ratio W_0/E_p then turns out to be of order 10. Hence 10- (or 100-) MG magnetic fields are easily generated. Clearly, the neutrino ponderomotive force driven magnetic fields are substantial and may account for the observed values in the neutrinosphere. We have thus offered a powerful mechanism that could be responsible for the intense supernovae magnetic fields.

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