Bull. Astr. Soc. India (2003) **31**, 363–364

The Magnetar Fields

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Abstract. We discuss the nature of evolution of the magnetic field in *magnetars*.

Keywords : magnetic fields–neutron stars: accretion–material flow

There is growing evidence that soft gamma-ray repeaters (SGR) and anomalous X-ray pulsars (AXP) are isolated neutron stars with super-strong magnetic fields ($\mathcal{B} > 10^{14}$G), known as *magnetars*. Recently, the detection of a 5 KeV absorption feature from SGR 1806-20 has been identified as proton cyclotron resonance, offering a direct measurement of the field to be $\sim 10^{15}$ G (Ibrahim, Swank & Parke 2003). Unlike rotation-powered pulsars magnetars are powered by the decay of the magnetic field. In this work we investigate the nature of this field evolution.

For such strong magnetic fields ($\mathcal{B} > \mathcal{B}_c, \mathcal{B}_c \sim 10^{14}G$ – electron critical field) all the electrons are confined to the ground Landau level. The ratio between the Landau level spacing ($E_{\rm LL}$), near the ground state, and the Fermi energy ($E_{\rm F}$), for relativistic electrons, has the following dependence on the density and the magnetic field,

$$\frac{E_F}{\Delta E_{\rm LL}} \sim 5 \times 10^4 \mu^{-2/3} \rho_{15}^{2/3} \mathcal{B}_{15}^{-1}, \quad (\rho = \rho_{15} 10^{15} {\rm g\,cm^{-3}}, \mathcal{B} = \mathcal{B}_{15} 10^{15}\ {\rm G}), \tag{1}$$

where μ is the mean molecular weight per electron. As seen from Fig.1A, this ratio is close to unity for a large range of densities where the quantum Hall regime prevails. The transport properties are highly anisotropic as well as field-dependent in such strongly quantizing fields (Yakovlev, 1984; Ghosh et al, 2002). Consequently, the time-scale of field decay ($\tau_o = c^2/4\pi\sigma, \sigma$ – electrical conductivity), due to pure ohmic dissipation, becomes field-dependent as shown in Fig. 1B. However, phenomenologically we expect the field to decay faster for stronger fields and the decay time-scale should become independent of the field strength as it approaches the canonical radio pulsar values ($\mathcal{B} \sim 10^{12}$ G). Therefore, the effective decay time-scale should be more like the dashed curve in Fig. 1B.

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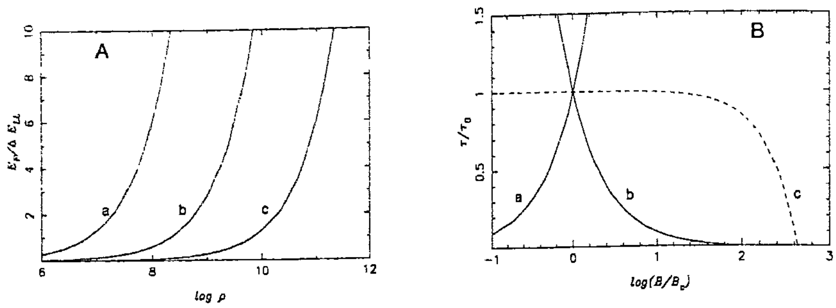

Figure 1. (A) - Ratio of Fermi Energy to Landau level spacing for electrons. Curves a, b, c correspond to $B = 10^{14}, 10^{15}, 10^{16}$ G. (B) - Ratio of strong-field ohmic dissipation time-scale to that for zero magnetic field. Curves a, b correspond to conductivities taken from Yakovlev (1984) and Ghosh et al. (2002). Curve c shows the expected behaviour.

As the crustal lattice yields under the pressure exerted by a $\sim 10^{15}$ G field, the currents need to be anchored in the stellar core, comprising of an n-p-e plasma. Assuming the plasma to be non-superfluid the evolution of the magnetic field would be governed by the induction equation (Goldreich & Reisenegger, 1992)

$$\frac{\partial \mathbf{B}}{\partial t} = -c\nabla \times \left(\frac{\mathbf{J}}{\sigma(\mathcal{B}=0)}\right) + \nabla \times (\mathbf{v} \times \mathbf{B}) - \frac{m_p/\tau_{pn} - m_e/\tau_{en}}{m_p/\tau_{pn} + m_e/\tau_{en}} \nabla \times \left(\frac{\mathbf{J} \times \mathbf{B}}{n_e}\right), \qquad (2)$$

where m, τ correspond to the masses and collision times for the relevant species of particles. Evidently, the second and the third terms corresponding to Hall drift and Ambipolar diffusion would be important for the magnetar field evolution, as pure ohmic diffusion does not have the phenomenologically expected characteristics. The anisotropy in the conductivity would give rise to strong Hall currents inducing rapid transfer of energy from dipolar component of the field to higher multi-poles. Since, currents of higher order multi-poles dissipate faster (Mitra, Konar & Bhattacharya 1999) the field would decay rapidly because of this. This work is in progress and the details would be reported in a future publication.

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