Magnetic Energy Dissipation in the Outer Crust of Neutron Stars

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Pushed by the accumulating observations of radio pulsars and accreting neutron stars (NSs), extensive studies have been performed to understand the evolution of magnetic fields in neutron stars. The radio pulsars are generally categorized into two classes: young ($< 10^7$ yr) pulsars with the magnetic field strength $B \simeq 10^{10\sim13}$ G, and the old millisecond radio pulsars, which have magnetic field strength as low as $10^{8\sim9}$ G. While most radio pulsars are isolated objects, the millisecond pulsars are predominantly in binaries, suggesting that the magnetic fields decay with time, perhaps by an accretion of matter from the binary companion.

For the isolated radio pulsars, it remains as an open question whether the NS magnetic fields do or do not decay with time. Recently, the discovery of magnetars, which would be a isolated NS with stronger magnetic fields ($B \sim 10^{15}$ G) has provided evidences for magnetic energy dissipation in neutron star[1], whose timescale is ~10 Myr[2]. At present, these ideas and new observations seem to favor the existence of the magnetic field decay in the isolated NSs.

Goldreich & Reisenegger[3] proposed a pioneering model of the magnetic field decay inside NSs, in which the large scale magnetic field is affected by the Hall turbulence. The magnetic energy is transported to the smaller scale due to the Hall cascade, leading to the dissipation via the Ohmic dissipation. The existence of Hall turbulence and the cascading process are numerically confirmed by electron Magnetohydrodynamic (EMHD) simulations[4]. However, the dissipation process, which should govern the magnetic field decay in NSs, cannot be treated consistently due to the MHD approximations.

In this paper, we perform Particle-In-Cell (PIC) simulations aiming to understand the decaying process in NSs[5]. Since the Maxwell equations and the equations of motion of plasma particles are consistently solved in PIC simulations, we can study the dissipation process without introducing phenomenological parameter (i.e., the electric resistivity).

Figure 1 shows numerical results of PIC simulations. Color shows the magnetic energy of turbulent fields and white curves denote for the magnetic field lines at the initial (left) and final (right) states. The initial magnetic field is consist of the uniform field that models the global field penetrating the NS and of the turbulent field that would be originated from the Hall cascade. The energy of initially imposed turbulent field is transported to the smaller scale through whistler waves. Since whistler waves propagate almost parallel to the global magnetic field lines, the cascading process becomes anisotropic. When the turbulent energy is cascaded down to the electron inertial scale, the magnetic energy is dissipated and the electrons are heated. The electrons with lower energy are heated in parallel to the magnetic field due to the Landau damping, while the electrons with higher energy is heated perpendicular to the magnetic field lines due to the cyclotron resonance. These two dissipation mechanisms make the electron distribution function anisotropic. Such the anisotropy of electron temperature is observed in magnetars, suggesting that the plasmas near the surface of NSs is heated by dissipation processes described above. Since the time scale of these dissipation processes is much shorter than the observed decay timescale, we speculate that the decay time scale is determined by the cascading time.

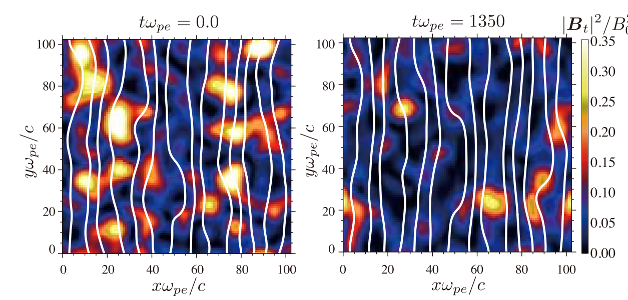

Figure 1: Numerical results of PIC simulations. Color and curves show the turbulent magnetic field energy and magnetic field lines at the initial (left) and final (right) states.

References

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