High Energy Processes and Phenomena in Astrophysics
IAU Symposium, Vol. 214, 2003
X. D. Li, V. Trimble, and Z. R. Wang, eds.

Pulsar Spin-Down by $^3P_2$ Superfluid Neutrons

Xin-Lian Luo, Qiu-He Peng, Ming Zhang

Department of Astronomy, Nanjing University, Nanjing 210093, China

Chih-Kang Chou

Institute of Astronomy and Department of Physics, National Central University, Chung-Li Taiwan 32054, China Taipei

Abstract. To describe pulsar spin-down, a simple combined torque model, that takes into account both the standard magnetic dipole radiation and the electromagnetic radiation from the $^3P_2$ superfluid vortex neutrons inside neutron star, is presented. Using an ordinary exponential model for the magnetic field decay, we investigate pulsar evolution tracks on the P-$\dot{P}$ diagram, which is quite different from that of the standard magnetic dipole radiation model, especially when the superfluid torque or field decay become dominate.

1. Introduction

Although there is no direct evidence that Neutron Stars (NSs) contain a liquid interior of superfluid neutrons and superconducting protons, nevertheless, this idea is strongly supported by the success of the BCS theory of superconductivity. Furthermore, the superfluid neutrons were successfully used to explain the post glitch of some pulsars by the transfer of angular momentum from superfluid nuclei to the coexisting lattice nuclei in the crust.

On the basis of the existence of superfluid neutrons, a different macroscopical effect of superfluid neutrons inside NSs was proposed by Peng et al. (1982) and Huang et al. (1982) two decades ago. The superfluid vortex neutrons may emit neutrinos and electromagnetic waves at the cost of the decrease of global rotation energy, which provides an additional torque for pulsar spin-down besides the standard magnetic dipole radiation.

2. Combined Model for Pulsar Spin-Down

First, combining the total radiation power form $^3P_2$ superfluid neutrons inside NS with the standard magnetic dipole radiation, we can get a very convenient form for pulsar spin-down, $\dot{P} = A\,(1 + aP^3)/P$, where $A = 9.77 \times 10^{-16}\,\mathrm{s}\,R_{s6}^6\,B_{s12}^2\,I_{45}^{-1}$ is connected with the poler magnetic field strength at pulsar surface, a is an introduced parameter related to the superfluid torque. Then, for simplicity, we adopt the widely used form, i.e. an exponential field decay model $B(t) = B_0 \cdot e^{-t/\tau_d}$ here, τ_d is the time scale for field decay, $B(t)$ and B_0

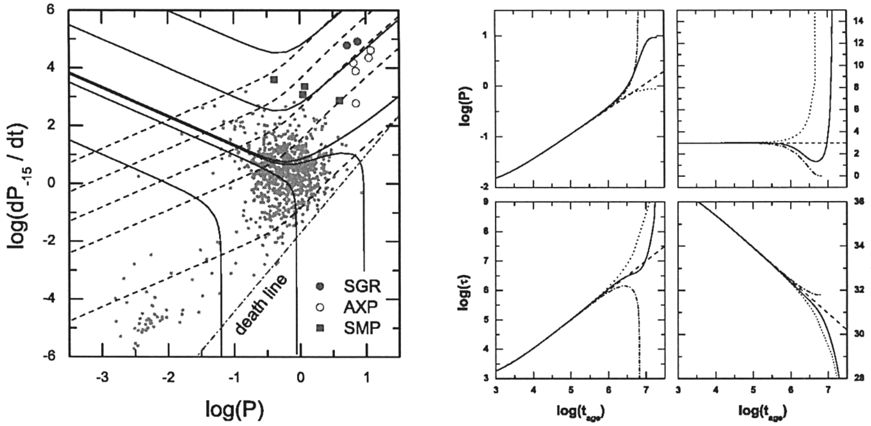

Figure 1. **Left:** Distribution of 845 pulsars without obvious accretion on the P-$\dot{P}$ diagram. The dots, filled circles, opened circles and filled squares represent normal pulsars, SGRs, AXPs and radio pulsars with strong magnetic field (SMPs), respectively. The solid lines show various evolutionary tracks on the P-$\dot{P}$ diagram with different initial magnetic field, from top to bottom corresponding to $B_0 = 10^{14}$, 10^{13}, 1.5×10^{12}, 1.4×10^{12}, 10^{12} and 10^{11} G. The short dashed lines represent equal age lines, from top to bottom corresponding to $t_{\rm age} = 10^3$, 10^4, 10^5, 10^6 and 10^7 yr. The dash-dotted line denotes the "death line" of pulsars. We have taken $a = 5$, $P_i = 0$ and $\tau_d = 4$ Myr above. **Right:** These four panels show period P, braking index n, characteristic age τ and braking torque N as function of true age $t_{\rm age}$. The solid line, the dotted line, the dashed line, and the dot-dashed line represent the results with different superfluid torque and time scale for field decay, *1)* $a = 5$, $\tau_{d7} = 0.4$, *2)* $a = 0$, $\tau_{d7} = 0.4$, *3)* $a = 0$, $\tau_{d7} \to \infty$, *4)* $a = 5$, $\tau_{d7} \to \infty$, respectively. We have taken $P_i = 0.01$ s, $B_0 = 1.4 \times 10^{12}$ G here.

are respectively the field strength at time t and the initial magnetic field. Now we can derive an analytical formulae for pulsar evolution tracks on the P-$\dot{P}$ diagram (Luo et al. 2002). The numerical results are show in Fig. 1.

3. Conclusions

It is obvious that there are three different kinds of tracks for pulsar evolution on the P-$\dot{P}$ diagram corresponding to pulsars with different initial magnetic field. If superfluid torque and field decay really play important roles in the dynamical evolution for pulsar spin down, pulsar evolution on the P-$\dot{P}$ diagram is quite different from that of the standard dipole radiation model. However, it is expected that the properties of the internal neutron superfluid vortex and the internal magnetic field of the NSs are very complicated and uncertain. It is worthwhile to improve this model by a more sophisticated approach and to investigate the superfluid vortex neutrons inside NSs by a more detailed rigorous computation in the future.

References

Huang, J. H. et al. 1982, A&A, 113, 9

Luo, X. L., Peng, Q. H. and Chou, C. K. 2002, Chin.Phys.Lett, Submitted

Peng, Q. H. et al. 1982, A&A, 107, 258