Radiation Recoil Velocity of a Neutron Star

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The 20th Anniversary of JGRG

&

The 60th Birthday of
Prof. Nakamura & Prof. Maeda

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Contents

High velocity of BH/NSs

as a consequence of violent event

- Comment on high velocity of BH by GW radiation

  Models + recent observation

- Proper motion of pulsars/magnetars

  Magnetic fields?

- Recoil velocity of a pulsar by EM radiation

  Shifted dipole Model (Harrison &Tademaru 1975)

  Model of magnetic dipole + quadrupole radiation

  (Y.K & Y. Kato 2010)

- Discussion

Runaway Black Hole by GW

Velocity by linear momentum radiation reaction

$$v = \Delta P_{GW} / M \approx \varepsilon(\Delta E_{GW} / Mc^2)c$$

- Quadrupole +Octapole Gravitational Radiation
  Bekenstein 1973 -…
- BH Perturbation 1983 - …
  Nakamura+Haugan+Sasaki+Oohara+Y.K.+….
- Numerical Relativity 2006 -…

  Baker et al …, Campanelli et al, +…

  Maximum velocity, ‘anti-kick’,…

Observational Evidence for High Velocity of BHs ?

e.g., Quasar E1821+643 @z=0.297

2100km/s

Robinson et al 2010

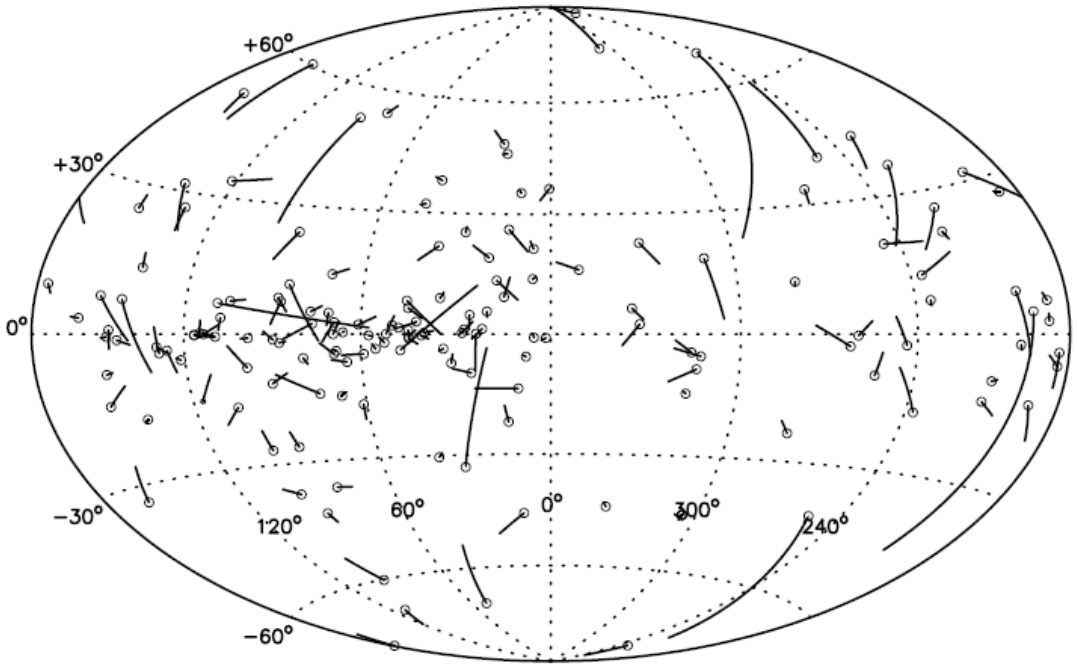
SDSS J1054.35+345631.3 @z=0.272

3500km/s

Shields et al 2009

- For super massive BH, GW recoil?
- For stellar mass BH, some ambiguity with SN

Proper Motion of PSRs



Proper motion by PSR timing methods,interferometers

Helfand, Taylor & Manchester (1977) for 5 PSRs

Hobbs et al (2005) for 233 PSRs

Velocity of PSR/Magnetars

Proper motion Hobbs et al (2005)

Mean 3D velocity is 400km/s

Fast moving pulsars

PSR2224+45(Cordes+1993) $v_\perp \approx 800 km/s$

B1508+55(Chatterjee+2005) $v_\perp \approx 1000 km/s$

Upper limits for magnetars

AXP XTEJ1810-197 $v_\perp < 210 km/s$

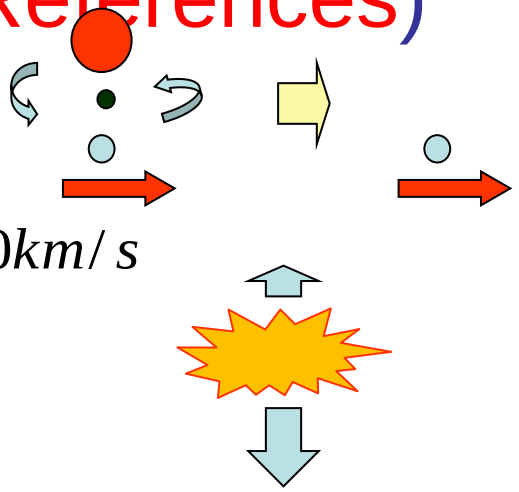
1E2259+586 $v_\perp < 1300 km/s$

SGR 1900+14 $v_\perp < 930 km/s$

(Helfand+2007, Kaplan+ 2009…)

Kick Velocity of Pulsars

Proposed Mechanisms （No References)



- Pre-natal scenario

  Collapse of binary $v \approx (GM/R)^{1/2} \approx 100 km/s$

- Natal scenario

  Asymmetry of SN explosion

  Neutrinos/(Magneto-) Hydrodynamical waves

- Post-natal scenario

  EM radiation and its recoil

Magnetic fields

Kick Velocity caused by Magnetic Fields

Asymmetry of SN explosion

Neutrinos/(Magneto-) Hydrodynamical waves

Strong field strength $B \approx 10^{15} G$

EM-radiation and its recoil

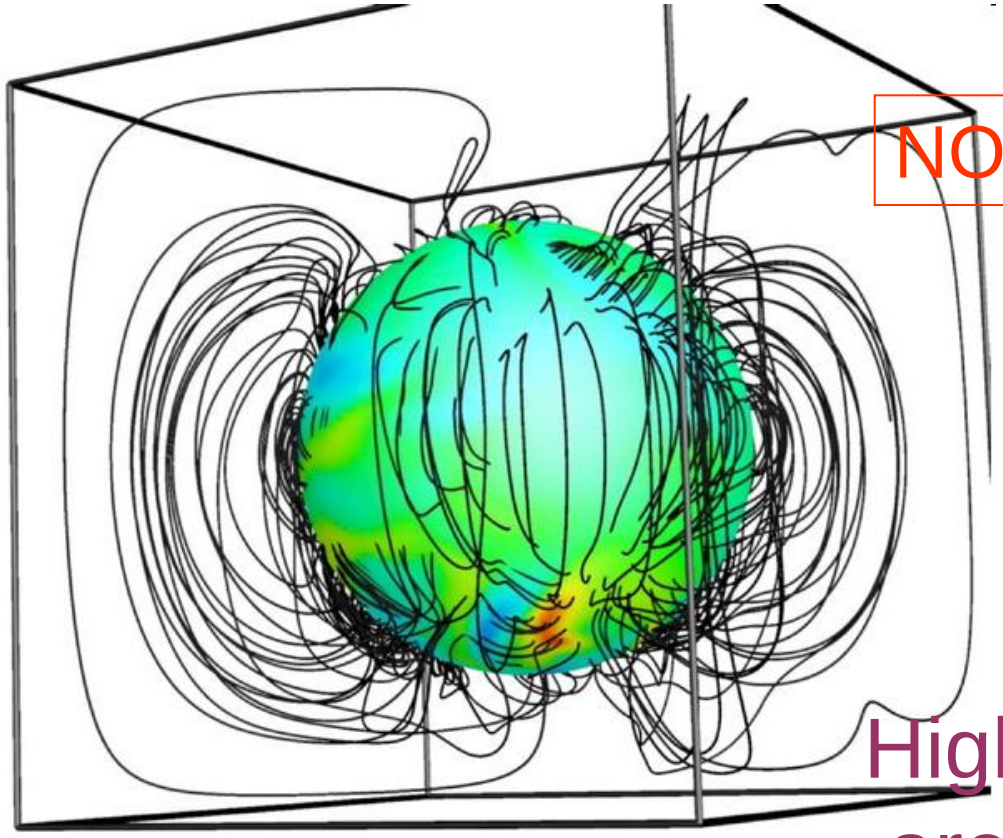
Field configuration

- When and how is the (strong) magnetic field generated? Fossil or dynamo?
- Upper limit for magnetars means no importance? Complicated?

Strength & configuration of magnetic fields in newborn NS

Strong magnetic fields generated by dynamo

Global Simulation of Dynamo for Fully Convective Rotating Stars



NOT Neutron Star

Higher multipoles are generated.

Saturated at $t \approx 10^3 (GM/R^3)^{-1/2}$

W. Dobler et. al., (2006) ApJ368, 336

Strength & configuration of magnetic fields in newborn NS

Strong magnetic fields generated by dynamo

(Thompson & Duncan 1993
Bonanno, Urpin & Belvedere 2006)

- For a fast rotator, strong ordered fields are generated.
- Maximum strength decreases, and higher mulitipole (small scale) fields dominate with decrease of initial spin.
  Almost dipole field in manetars, but dipole field + higher mulitipoles in PSRs

Recoil Velocity by Radiation

Radiation of (GW/EM) waves $h \propto \sum (A_{lm} Y_{lm})$

- Energy is an incoherent sum

Strength

$$dE/dt \propto \int d\Omega \sum (A_{lm} Y_{lm}) \sum (A_{lm} Y_{lm})^*$$
$$\propto \sum |A_{lm}|^2$$

- In linear momentum radiation, interference is important

$$d\vec{P}/dt \propto \int d\Omega \sum (A_{lm} Y_{lm}) \vec{n} \sum (A_{lm} Y_{lm})$$
$$dP_z/dt \propto \int d\Omega \sum (A_{lm} Y_{lm}) \cos\theta \sum (A_{lm} Y_{lm})^*$$

Configuration

$$\propto \sum C_l A_{lm} A_{l\pm 1m}{}^*$$

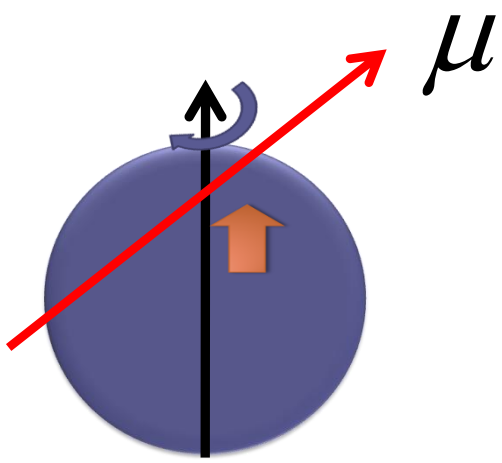
Off-center Dipole Model

Harrison &Tademaru (1975)ApJ 201, 447

(Lai et al (2001) ApJ 549, 1111)

- Dipole shifted from center by s
- Nonzero momentum by

up-down asymmetry of B



Quadrupole moment

$$Q \approx \mu s \qquad s < R$$

$$\Delta P \propto \mu Q \times \Omega^5$$

? Much larger Q

Dipole and Quarupole Radiation

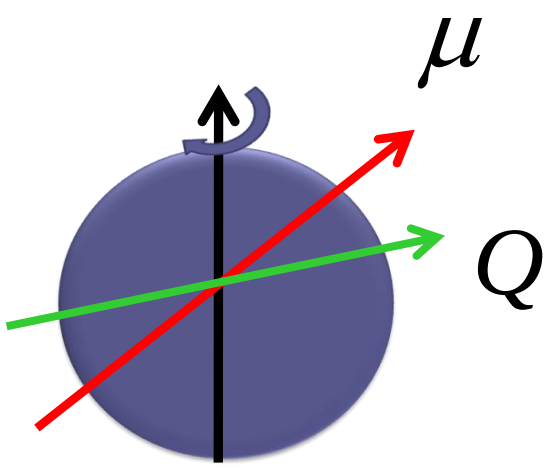
- Large quadrupole moment $Q > Q_B \equiv \mu R$
- But, weak constraint in present slow rotating phase $Q < Q_s \equiv \mu c / \Omega_0$

Spindown is given by $L_l \propto (\Omega / c)^{2l+2} M_l^{\ 2}$

$M_1 = \mu, M_2 = Q, \ldots$

Model of Dipole plus Quradrupole Radiation

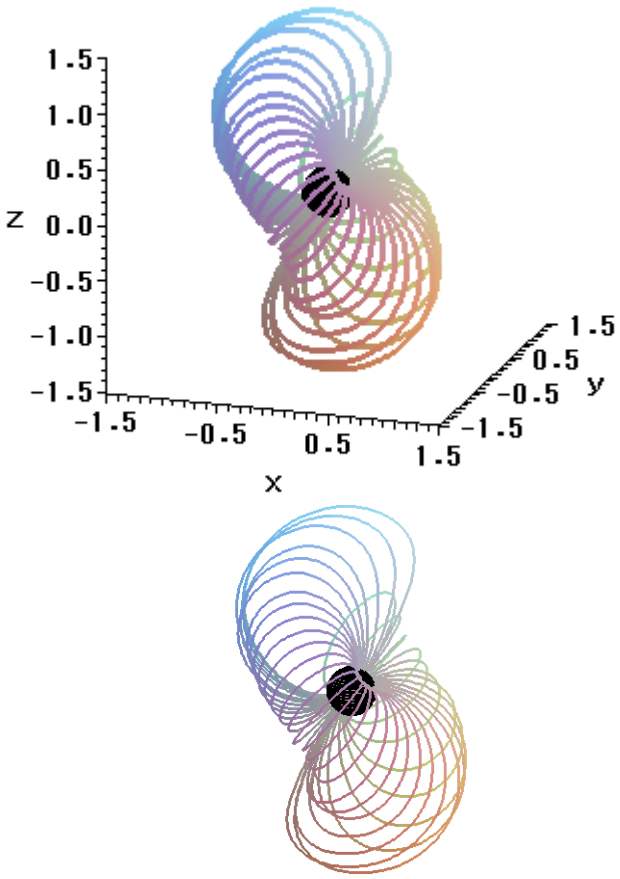
- Paramters
  - Strength μ, Q
  - Configuration χ_1, χ_2, δ



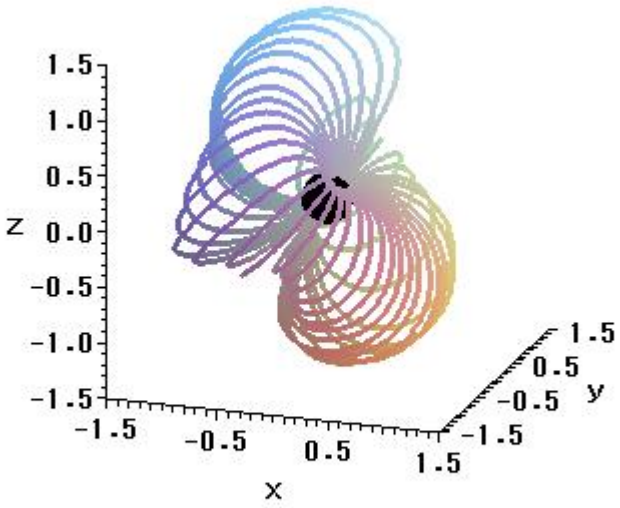
- Magnetic radiation M(l,m)
  M(1,1), M(2,1),M(2,2)

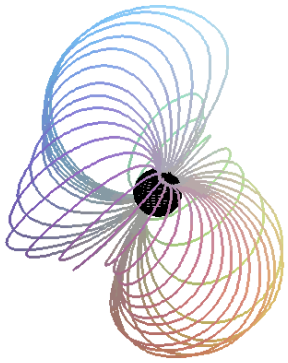
- Off-center Dipole
  M(1,1),M(2,1),E(1,1)

Global Structure of Closed Field Lines near Light Cylinder



Pure Dipole





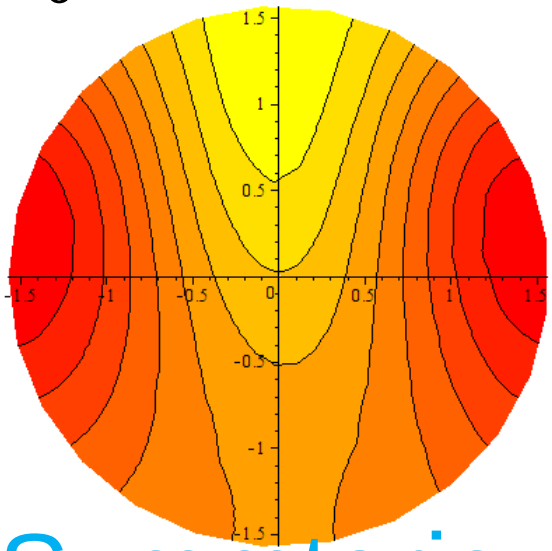
Dipole + Quadrupole

Symmetry of Radiation Partern

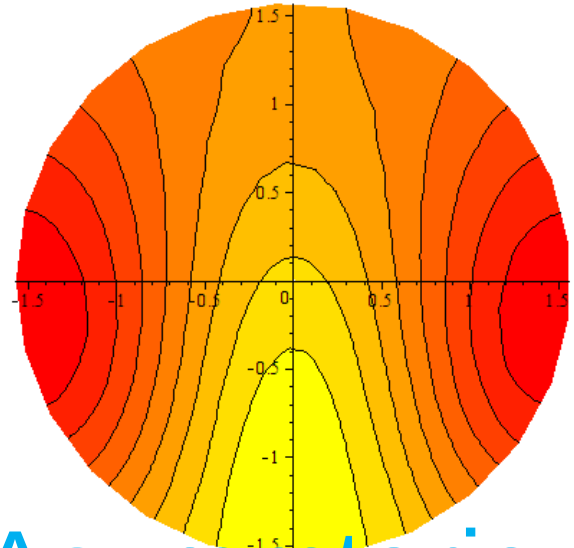
$\delta = 0$

Poynting flux

$\delta = \pi / 2$

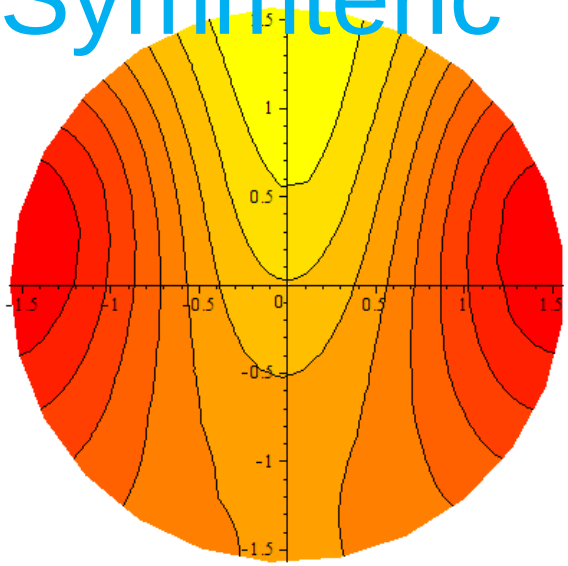


+z

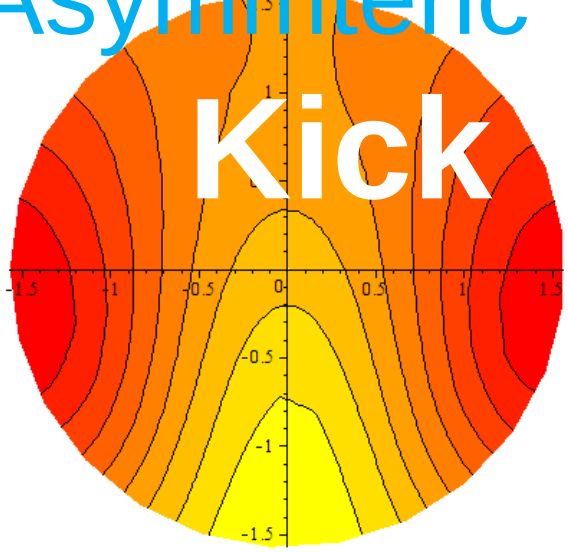


Symmteric

Asymmteric



-z



Kick

Radiation Loss and Evolution

- Energy loss determines the spin evolution. $\frac{d\Omega}{dt}$

$$L = \int \frac{c}{4\pi} \overline{(\mathbf{E} \times \mathbf{B})} \cdot \mathbf{e}_r r^2 \sin\theta d\theta d\phi$$

$$= \frac{2\mu^2\Omega^4}{3c^3} \sin^2\chi_1 + \frac{Q^2\Omega^6}{160c^5} \sin^2 2\chi_2 + \frac{2Q^2\Omega^6}{5c^5} \sin^4\chi_2$$

M(1,1) M(2,1) M(2,2)

- Momentum loss determines the acceleration. $\frac{dV}{dt}$

$$F = \int \frac{1}{4\pi} \overline{(\mathbf{E} \times \mathbf{B})} \cdot \mathbf{e}_z r^2 \sin\theta d\theta d\phi = \frac{\mu Q \Omega^5}{20c^5} \sin\chi_1 \sin 2\chi_2 \sin\delta.$$

M(1,1) x M(2,1)

- Kinetic velocity is given by

$$V = \int I\Omega F/(ML) d\Omega \propto \langle \frac{\Delta P}{\Delta E} \rangle \frac{E_{rot}}{M}$$

Efficient Configuration

$$V \propto \langle \frac{\Delta P}{\Delta E} \rangle \frac{E_{rot}}{M} \propto \Omega_i^2 \propto P_i^{-2}$$

- Large momentum radiation
  - Orthogonal dipole and quadrupole planes

$$\delta = \pi / 2$$

- Small M(2,2) radiation
  - Small inclination angle
  - Almost axially symmetric quadrupole field

$$\chi_2 \approx 0$$

- Maximum velocity at $Q \approx \mu c / \Omega_i$

$$V = 930 (P_i / 1ms)^{-2} \, km/s$$

Summary

Kick velocity by rotating magnetic dipole and quadrupole moments

- Strong field is NOT necessary
- Configuration is important

➢ Slow velocity of magnetar with almost diople

➢ High velocity of PSR with large quadrupole

- Or magnetic field is not relevant?

Final Remaks

- Porper motion is a relic of violent event
- Direct observation by GWs, GRBs

LCGT soon!

We hope better understanding of the relativistic astrophysics by the next anniversary of JGRG meeting