Chapter 1

PHYSICS OF NEUTRON STAR KICKS

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Abstract

It is no longer necessary to “sell” the idea of pulsar kicks, the notion that neutron stars receive a large velocity (a few hundred to a thousand km s$^{-1}$) at birth. However, the origin of the kicks remains mysterious. We review the physics of different kick mechanisms, including hydrodynamically driven, neutrino and magnetically driven kicks.

1. INTRODUCTION

It has long been recognized that neutron stars have space velocities much greater than their progenitors’. Recent studies of pulsar proper motion give 200 – 500 km s$^{-1}$ as the mean 3D velocity of NSs at birth (e.g., Lyne and Lorimer 1994; Lorimer et al. 1997; Hansen & Phinney 1997; Cordes & Chernoff 1998), with possibly a significant population having velocities greater than 700 km s$^{-1}$. Direct evidence for pulsar velocities $\geq$1000 km s$^{-1}$ comes from observations of the bow shock produced by the Guitar Nebula pulsar (B2224+65) in the interstellar medium (Cordes et al. 1993) and studies of pulsar-supernova remnant associations (e.g., Frail et al. 1994; Kaspi 1999). A natural explanation for such high velocities is that supernova explosions are asymmetric, and provide kicks to nascent neutron stars. Support for supernova kicks has come from the detection of geodetic precession in binary pulsar PSR 1913+16 (Cordes et al. 1990; Kramer 1998; Wex et al. 1999) and the orbital plane precession in PSR J0045-7319/B-star binary (Kaspi et al. 1996) and its fast orbital decay (which indicates retrograde rotation of the B star with respect to the orbit; Lai 1996); These results demonstrate that binary break-up (as originally suggested by Gott et al. 1970; see Iben & Tutukov 1996) can not be solely responsible for the observed pulsar velocities, and that natal kicks are required. Evolutionary studies of neutron star binary population also imply the existence of pulsar kicks (e.g., Fryer et al. 1998). Finally, there are
many direct observations of nearby supernovae (e.g., Wang et al. 1999) and supernova remnants which support the notion that supernova explosions are not spherically symmetric.

Despite decades of theoretical investigations, our understanding of the physical mechanisms of core-collapse supernovae remains significantly incomplete. While there is a consensus that neutrino heating of the stalled shock (0.1 − 1 s after bounce) plays an important role in driving the explosion, it is unclear whether the heating is sufficient to produce the observed supernova energetics; it is also unclear whether any convective motion or hydrodynamical instability is central to the explosion mechanism (e.g., Herant et al. 1994; Burrows et al. 1995; Janka & Müller 1996; Mezzacappa et al. 1998). The prevalence of neutron star kicks poses a significant mystery, and indicates that large-scale, global deviation from spherical symmetry is an important ingredient in any successful theory of core-collapse supernovae.

In this paper, we concentrate on different classes of physical mechanisms for generating neutron star kicks (§§2-4), and then briefly discuss the astrophysical/observational implications (§5).

2. HYDRODYNAMICALLY DRIVEN KICKS

The collapsed stellar core and its surrounding mantle are susceptible to a variety of hydrodynamical (convective) instabilities (e.g., Herant et al. 1994; Burrows et al. 1995; Janka & Müller 1996; Keil et al. 1996). It is natural to expect that the asymmetries in the density, temperature and velocity distributions associated with the instabilities can lead to asymmetric matter ejection and/or asymmetric neutrino emission. Numerical simulations, however, indicate that the local, post-collapse instabilities are not adequate to account for kick velocities $\sim 100$ km s$^{-1}$ (Janka & Müller 1994; Burrows & Hayes 1996; Janka 1998) — These simulations were done in 2D, and it is expected that the flow will be smoother on large scale in 3D simulations, and the resulting kick velocity will be even smaller.

Global asymmetric perturbations in presupernova cores are required to produce the observed kicks hydrodynamically (Goldreich et al. 1996). Numerical simulations by Burrows & Hayes (1996) demonstrate that if the precollapse core is mildly asymmetric, the newly formed neutron star can receive a kick velocity comparable to the observed values. (In one simulation, the density of the collapsing core exterior to 0.9$M_\odot$ and within 20° of the pole is artificially reduced by 20%, and the resulting kick is about 500 km s$^{-1}$.) Asymmetric motion of the exploding material (since the shock tends to propagate more “easily” through the low-density region) dominates the kick, although there is also contribution (about 10 − 20%) from asymmetric neutrino emission. The magnitude of kick velocity is proportional to the degree of initial asymmetry in
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Figure 1.1  Propagation diagram computed for a $15M_\odot$ presupernova model of Weaver and Woosley (1993). The solid curve shows $N^2$, where $N$ is the Brunt-Väisälä frequency; the dashed curves show $L_1^2$, where $L_1$ is the acoustic cutoff frequency, with $l = 1, 2, 3$. The spikes in $N^2$ result from discontinuities in entropy and composition. The iron core boundary is located at $1.3 M_\odot$, the mass-cut at $1.42 M_\odot$. Convective regions correspond to $N = 0$. Gravity modes (with mode frequency $\omega$) propagate in regions where $\omega < N$ and $\omega < L_1$, while pressure modes propagate in regions where $\omega > N$ and $\omega > L_1$. Note that a g-mode trapped in the core can lose energy by penetrating the evanescent zones and turning into an outgoing acoustic wave (see the horizontal line). Also note that g-modes with higher $n$ (the radial order) and $l$ (the angular degree) are better trapped in the core than those with lower $n$ and $l$.

the imploding core. Thus the important question is: What is the origin of the initial asymmetry?

(i) Presupernova Perturbations

Goldreich et al. (1996) suggested that overstable g-mode oscillations in the presupernova core may provide a natural seed for the initial asymmetry. These overstable g-modes arise as follows. A few hours prior to core collapse, a massive star ($M > \sim 8 M_\odot$) has gone through a successive stages of nuclear burning, and attained a configuration with a degenerate iron core overlaid by an “onion skin” mantle of lighter elements. The rapidly growing iron core is encased in and fed by shells of burning silicon and oxygen, and the entire assemblage is surrounded by a thick convection zone. The nearly isothermal core is stably stratified and supports internal gravity waves. These waves cannot propagate in the unstably stratified convection zone, hence they are trapped and give rise to core g-modes in which the core oscillates with respect to the outer parts of the star. The overstability of the g-mode is due to the “$\varepsilon$-mechanism” with driving provided by temperature sensitive nuclear burning in Si and O shells surrounding the core before it implodes. It is simplest to see this by considering a $l = 1$ mode: If we perturb the core to the right, the right-hand-side of the shell will be compressed, resulting in an increase in temperature; Since the shell nuclear burning rate depends sensitively on temperature (power-law index $\sim 47$ for Si burning and $\sim 33$ for O burning), the nuclear burning is
greatly enhanced; This generates a large local pressure, pushing the core back
to the left. The result is an oscillating g-mode with increasing amplitude.

The main damping mechanism comes from the leakage of mode energy. The
local (WKB) dispersion relation for nonradial waves is

\[ k_r^2 = (\omega^2 c_s^2)^{-1} (\omega^2 - L_l^2)(\omega^2 - N^2), \]

where \( k_r \) is the radial wavenumber, \( L_l = \sqrt{l(l+1)}c_s/r \) (\( c_s \) is the sound
speed) and \( N \) are the acoustic cut-off (Lamb) frequency and the Brunt-Väisälä
frequency, respectively. Since acoustic waves whose frequencies lie above
the acoustic cutoff can propagate through convective regions, each core g-
mode will couple to an outgoing acoustic wave, which drains energy from the
core g-modes (see Fig. 1.1). This leakage of mode energy can be handled
with an outgoing propagation boundary condition in the mode calculation.
Also, neutrino cooling tends to damp the mode. Since the nuclear energy
generation rate depends more sensitively on temperature than pair neutrino
emission (power law index \( \sim 9 \)), cooling is never comparable to nuclear heating
locally. Instead, thermal balance is mediated by the convective transport of
energy from the shells, where the rate of nuclear energy generation exceeds
that of neutrino energy emission, to the cooler surroundings where the bulk
of the neutrino emission takes place. Calculations (based on the \( 15M_\odot \) and
\( 25M_\odot \) presupernova models of Weaver & Woosley 1993) indicate that a large
number of g-modes are overstable, although for low-order modes (small \( l \) and
\( n \)) the results depend sensitively on the detailed structure and burning rates
of the presupernova models (Lai & Goldreich 2000b, in preparation).

Our tentative conclusion is that overstable g-modes can potentially grow to
large amplitudes prior to core implosion, although a complete understanding of
the global pre-collapse asymmetries is probably out of reach at present, given
the various uncertainties in the presupernova models (see Bazan & Arnett 1998
for complications due to convective shell burning in presupernova stars).

(ii) Amplification of Perturbation During Core Collapse

Core collapse proceeds in a self-similar fashion, with the inner core shrinking
subsonically and the outer core falling supersonically at about half free-fall
speed (Goldreich & Weber 1980; Yahil 1983). The inner core is stable to
non-radial perturbations because of the significant role played by pressure in
its subsonic collapse. Pressure is less important in the outer region, making
it more susceptible to large scale instability. A recent stability analysis of
Yahil’s self-similar collapse solution (which is based on Newtonian theory
and a polytropic equation of state \( P \propto \rho^\Gamma \), with \( \Gamma \sim 1.3 \)) does not reveal any
unstable global mode before the proto-neutron star forms (Lai 2000). However,
during the subsequent accretion of the outer core (involving 15\% of the core
mass) and envelope onto the proto-neutron star, nonspherical perturbations
can grow according to \( \delta \rho/\rho \propto r^{-1/2} \) or even \( \delta \rho/\rho \propto r^{-1} \) (Lai & Goldreich
The asymmetric density perturbations seeded in the presupernova star, especially those in the outer region of the iron core, are therefore amplified (by a factor of 5-10) during collapse. The enhanced asymmetric density perturbation may lead to asymmetric shock propagation and breakout, which then give rise to asymmetry in the explosion and a kick velocity to the neutron star (Goldreich et al. 1996; Burrows & Hayes 1996).

3. NEUTRINO DRIVEN KICKS

The second class of kick mechanisms rely on asymmetric neutrino emission induced by strong magnetic fields. The fractional asymmetry $\alpha$ in the radiated neutrino energy required to generate a kick velocity $v_{\text{kick}}$ is $\alpha = Mv_{\text{kick}}c/E_{\text{tot}}$ ($= 0.028$ for $v_{\text{kick}} = 1000$ km s$^{-1}$, neutron star mass $M = 1.4 M_\odot$ and total neutrino energy radiated $E_{\text{tot}} = 3 \times 10^{53}$ erg).

(i) Effect of Parity Violation

Because weak interaction is parity violating, the neutrino opacities and emissivities in a magnetized nuclear medium depend asymmetrically on the directions of neutrino momenta with respect to the magnetic field, and this can give rise to asymmetric neutrino emission from the proto-neutron star. Chugai (1984) (who gave an incorrect expression for the electron polarization in the relativistic, degenerate regime) and Vilenkin (1995) considered neutrino-electron scattering, but this is less important than neutrino-nucleon scattering in determining neutrino transport in proto-neutron stars. Dorofeev et al. (1985) considered neutrino emission by Urca processes, but failed to recognize that in the bulk interior of the star the asymmetry in neutrino emission is cancelled by that associated with neutrino absorption (Lai & Qian 1998a).

Horowitz & Li (1998) suggested that large asymmetries in the neutrino flux could result from the cumulative effect of multiple scatterings of neutrinos by slightly polarized nucleons (see also Janka 1998; Lai & Qian 1998a). However, it can be shown that, although the scattering cross-section is asymmetric with respect to the magnetic field for individual neutrinos, detailed balance requires that there be no cumulative effect associated with multiple scatterings in the bulk interior of the star where the asymmetry in neutrino emission is cancelled by that associated with neutrino absorption (Lai & Qian 1998a).

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For a given neutrino species, there is a drift flux of neutrinos along the magnetic field in addition to the usual diffusive flux. This drift flux depends on the deviation of the neutrino distribution function from thermal equilibrium. Thus asymmetric neutrino flux can be generated in the outer region of the proto-neutron star (i.e., above the neutrino-matter decoupling layer, but below the neutrinosphere) where the neutrino distribution deviates significantly from thermal equilibrium. While the drift flux associated with $\nu_\mu$'s and $\bar{\nu}_\tau$'s is exactly canceled by that associated with $\bar{\nu}_\mu$'s and $\nu_\tau$'s, there is a net drift flux due to $\nu_e$'s and $\bar{\nu}_e$'s.
Arras & Lai (1999b) found that the asymmetry parameter for the $\nu_e$-$\bar{\nu}_e$ flux is dominated for low energy neutrinos ($\lesssim 15$ MeV) by the effect of ground (Landau) state electrons in the absorption opacity, $\epsilon_{\text{abs}} \simeq 0.6 B_{15} (E_{\nu}/1 \text{ MeV})^{-2}$, where $B_{15} = B/(10^{15} \text{ G})$, and for high energy neutrinos by nucleon polarization ($\sim \mu_{\mu} B/T$). Averaging over all neutrino species, the total asymmetry in neutrino flux is of order $\alpha \sim 0.2 \epsilon_{\text{abs}}$, and the resulting kick velocity $v_{\text{kick}} \sim 50 B_{15} \text{ km s}^{-1}$. There is probably a factor of 3 uncertainty in this estimate. To firm up this estimate requires solving the neutrino transport equations in the presence of parity violation for realistic proto-neutron stars.

(ii) Effect of Asymmetric Field Topology

A different kick mechanism relies on the asymmetric magnetic field distribution in proto-neutron stars (see Bisnovatyi-Kogan 1993; However, he considered neutron decay, which is not directly relevant for neutrino emission from proto-neutron stars). Since the cross section for $\nu_e$ ($\bar{\nu}_e$) absorption on neutrons (protons) depends on the local magnetic field strength due to the quantization of energy levels for the $e^-$ ($e^+$) produced in the final state, the local neutrino fluxes emerged from different regions of the stellar surface are different. Calculations indicate that to generate a kick velocity of $\sim 300 \text{ km s}^{-1}$ using this mechanism alone would require that the difference in the field strengths at the two opposite poles of the star be at least $10^{16} \text{ G}$ (Lai & Qian 1998b). Note that unlike the kick due to parity violation [see (i)], this mechanism does not require the magnetic field to be ordered, i.e., only the magnitude of the field matters.

(iii) Exotic Neutrino Physics

There have also been several interesting ideas on pulsar kicks which rely on nonstandard neutrino physics. It was suggested (Kusenko & Segre 1996) that asymmetric $\nu_\tau$ emission could result from the Mikheyev-Smirnov-Wolfenstein flavor transformation between $\nu_\tau$ and $\nu_e$ inside a magnetized proto-neutron star because a magnetic field changes the resonance condition for the flavor transformation. This mechanism requires neutrino mass of order 100 eV. Another similar idea (Akhmedov et al. 1997) relies on both the neutrino mass and the neutrino magnetic moment to facilitate the flavor transformation. More detailed analysis of neutrino transport (Janka & Raffelt 1998), however, indicates that even with favorable neutrino parameters (such as mass and magnetic moment) for neutrino oscillation, the induced pulsar kick is much smaller than previously estimated (i.e., $B \gg 10^{15} \text{ G}$ is required to obtain 100 km s$^{-1}$ kick).

4. EM RADIATION DRIVEN KICKS

For completeness, we mention the post-explosion “rocket” effect due to electromagnetic (EM) radiation from off-centered magnetic dipole in the pulsar (Harrison & Tademaru 1975). In this mechanism, the neutron star velocity comes at the expense of its spin kinetic energy, which is radiated away asym-
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metrically via EM braking; The kick is attained on the timescale of the initial spindown time of the pulsar (i.e., this is not a “natal” kick). The neutron star velocity changes according to \( \dot{v} = \epsilon L/c \), where \( L \) is the EM braking power, and \( \epsilon \) is the asymmetry parameter. Typically, \( \epsilon \sim 0.1(\Omega s/c)(\mu_\phi/\mu_z) \), where \( \Omega \) is the spin and \( s \) is the “off-center” displacement of the dipole; In fact, there is theoretical maximum, \( \epsilon = 0.16 \), achieved for \( \mu_R = 0, \mu_\phi/\mu_z = 0.63(\Omega s/c) \) (where \( \mu_R, \mu_\phi, \mu_z \) are the three cylindrical components of the dipole). The kick velocity is along the spin axis, and \( v_{\text{kick}} \approx 600(\bar{\epsilon}/0.1)(\nu_0/1 \text{ kHz})^2 \text{ km s}^{-1} \) (where \( \nu_0 \) is the initial spin). Clearly, Even if the neutron star were born with maximum rotation rate and \( \epsilon \) were maintained at near the maximum value, the kick velocity would still be at most a few hundred km s\(^{-1}\). Given that most pulsars were born rotating slowly (see Spruit & Phinney 1998), we conclude that “EM rocket” cannot be the main mechanism for pulsar kicks.

5. DISCUSSION

Statistical studies of pulsar population have revealed no correlation between \( v_{\text{kick}} \) and magnetic field strength, or correlation between the kick direction and the spin axis (e.g., Lorimer et al. 1995; Cordes & Chernoff 1998; Deshpande et al. 1999). Given the large systematic uncertainties, the statistical results, by themselves, cannot reliably constrain any kick mechanism (see Cordes & Chernoff 1998). For example, the magnetic field strengths required for the neutrino-driven mechanisms are \( \gtrsim 10^{15} \text{ G} \), much larger than the currently inferred dipolar surface fields of typical radio pulsars; the internal magnetic fields of neutron stars and their evolution remain clouded in mystery; and several different mechanisms may contribute to the observed kick velocities.

It is of interest to note that soft gamma repeaters (“magnetars”: neutron stars with observed magnetic fields \( \gtrsim 10^{14} \text{ G} \); see Thompson & Duncan 1996) have very high velocities, \( \gtrsim 1000 \sim 2000 \text{ km s}^{-1} \) (e.g., Kaspi 1999; Marsden et al. 1999). Such a high velocity may well require superstrong magnetic fields (\( \gtrsim 10^{16} \text{ G} \)) to be present in the proto-neutron stars, although hydrodynamical effects remain a viable kick mechanism if enough presupernova asymmetry can be generated. It has recently been suggested that MHD jets can play an important role in supernovae (Khokhlov et al. 1999), but the origin of the jets is unknown, nor it is clear why the two opposite jets are so different (a necessary condition to produce a kick).

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