Core-Collapse Supernovae and Neutron Star Kicks

Dong Lai

Department of Astronomy, Cornell University, Ithaca, NY 14853, USA

Abstract. Recent observations have revealed many new puzzles related to core-collapse supernovae, including the formation of magnetars and black holes and their possible GRB connections. We review our current understanding of the origin of pulsar kicks and supernova asymmetry. It is argued that neutron star kicks are intimately connected to the other fundamental parameters of young neutron stars, such as the initial spin and magnetic field strength.

1. Introduction

The subject of supernovae (SNe) has a long history, but the modern era of SN research really began in 1934 when Baade and Zwicky made the prophetic suggestion that the death of massive stars, SN explosions and neutron star (NS) formation are connected events. This suggestion was confirmed by the discovery of the pulsar in the Crab supernova remnant (SNR) in 1968; the SN, as is well known, was actually observed in 1054 by Chinese astronomers.

Today the mechanism of SN explosion remains an unsolved problem. Moreover, observations over the last few years suggest that we may actually know less than we thought about core collapse and explosion of massive stars. Here we discuss a small sample of unsolved problems related to SNe and NS formation, focusing on the problem of NS kicks.

Basic Paradigm for Core-Collapse Supernovae: The current paradigm for core-collapse supernovae is that they are neutrino-driven (see, e.g., Bethe 1990; Janka et al. 2001; Burrows & Thompson 2002 for reviews): As the central core of a massive star collapses to nuclear density, it rebounds and sends off a shock wave, leaving behind a proto-NS. The shock stalls at several 100's km because of neutrino loss and nuclear dissociation in the shock. A fraction of the neutrinos emitted from the proto-NS get absorbed by nucleons behind the shock, thus reviving the shock, leading to an explosion on the timescale several 100's ms — This is the so-called “delayed mechanism”. However, 1D simulations with detailed neutrino transport seem to indicate that neutrino heating of the stalled shock, by itself, does not lead to a robust explosion (e.g., Rampp & Janka 2000; Liebendoerfer et al. 2002). It has been argued that neutrino-driven convection in the proto-NS (which tends to increase the neutrino flux) and that in the shocked mantle (which tends to increase the neutrino heating efficiency) are central to the explosion mechanism, although it is not clear how robust of these convections are (see, e.g., Mezzacappa et al. 1998; Fryer & Warren 2002). Clearly, in this
“standard model”, the problem of SN explosion is a quantitative one, involving 3D radiation (neutrino) (and possibly relativistic) hydrodynamics.

This basic picture of core-collapse SNe, however, is likely to be incomplete. There are some obvious puzzles as a result of recent observations:

**Formation of Magnetars:** Observations over the last few years have revealed two new classes of young NSs, the soft gamma-ray repeaters (SGRs) and anomalous X-ray pulsars (AXPs). They have many common characteristics and are mostly likely related to each other (see Kaspi’s contribution in this proceedings). Strong physical arguments suggest that these are young NSs endowed with superstrong magnetic fields $B > 10^{14}$ G (see Thompson 2001). The existence of these magnetars poses some obvious questions: Under what conditions core-collapse of massive stars will lead to radio pulsars vs. magnetars? What is the branching ratio? What is the origin of the NS magnetic field? Does the B-field (in combination with rotation) play any dynamical role in the explosion? Currently we do not have firm answers to these questions (see, e.g., Thompson & Duncan 1993).

**Black Hole Formation and Core-Collapse SNe:** BHs are also formed in the core collapse of massive stars. Recent observations showed that BH formation can be accompanied by SN explosion, at least in two cases: The companion of the BH X-ray binary GRO J1655-40 (Nova Sco) and that of SAX J1819.3-2525 (V4641 SGR) have high abundance of $\alpha$-elements (Israelian et al. 1999; Orosz et al. 2001); these $\alpha$-elements can only be produced in a SN explosion. Apparently, the companion stars have been polluted by material ejected in the SN that accompanied the formation of the BH primary (see Podsiadlowski et al. 2002). These observations pose a host of questions: What are the differences between a SN that made a NS and a SN that made a BH? How is the BH formed? We could have a direct collapse to BH in which the shock wave never successfully makes it to induce an explosion, or we could have an indirect process where a shock wave successfully makes an explosion and a NS forms temporarily followed by fall-back, or loss of angular momentum and thermal energy in the proto-NS which then collapses to a BH. This indirect process may explain the relatively large space velocity of GRO J1655-40.

On a more speculative side, there is possible connection between SN and the central engine of gamma-ray bursts (GRBs). In the last few years a growing list of observations suggests that some GRBs are connected with the death of massive star and SNe. The famous case is GRB 980425, which coincided both in time and in position with a Type Ic SN1998bw. In at least 3 GRBs (980326, 970228, 000911), the rebrightening of the optical afterglows about a month after the initial bursts have been observed and interpreted as the underlying SNe which emerged when the afterglows faded. Possible emission line features ($K_{\alpha}$ of Fe, O, Mg, Si, etc) in several X-ray afterglows at hours-days may also be an indication of SNe. The obvious question is: under what conditions will the collapse of a massive star lead to GRB, SN with BH, SN with NS, etc.?

2. **Evidence for Neutron Star Kicks and Supernova Asymmetry**

It has long been recognized that NSs have space velocities much greater than their progenitors’. A natural explanation for such high velocities is that SN
explosions are asymmetric, and provide kicks to the nascent NSs. In recent years evidence for NS kicks and SN asymmetry has become much stronger, but the origin of the kicks remains mysterious. The observations that support (or even require) NS kicks fall into three categories:

(1) Large NS Velocities ($\gg$ the progenitors’ velocities $\sim 30 \text{ km s}^{-1}$):
- The study of pulsar proper motion give a mean birth velocity $200 - 500 \text{ km s}^{-1}$ (Lorimer et al. 1997; Hansen & Phinney 1997; Arzoumanian et al 2002), with possibly a significant population having $V \gtrsim 1000 \text{ km s}^{-1}$.
- Observations of bow shock from the Guitar nebula pulsar (B2224+65) implies $V \gtrsim 1000 \text{ km s}^{-1}$ (Cordes et al. 1993; Chatterjee & Cordes 2002).
- The studies of NS – SNR associations have, in some cases, implied large NS velocities, up to $\sim 10^3 \text{ km s}^{-1}$ (e.g., NS in Cas A SNR has $V > 330 \text{ km s}^{-1}$; Thorstensen et al. 2001).

(2) Characteristics of NS Binaries: While large space velocities can in principle be accounted for by binary break-up, many observed characteristics of NS binaries can only be explained by intrinsic kicks:
- The detection of geodetic precession in binary pulsar PSR 1913+16 (Kramer 1998; Wex et al. 1999; see contributions by J. Weisberg and by M. Kramer).
- The spin-orbit misalignment in PSR J0045-7319/B-star binary, as manifested by the orbital plane precession (Kaspi et al. 1996; Lai et al. 1995) and fast orbital decay (which indicates retrograde rotation of the B star with respect to the orbit; Lai 1996a; Kumar & Quataert 1997). Similar precession of orbital plane has been observed in PSR J1740-3052 system (see Stair’s contribution).
- High system radial velocity ($430 \text{ km s}^{-1}$) of X-ray binary Circinus X-1 (Tauris et al. 1999). Also, PSR J1141-6545 has $V_{\text{sys}} \simeq 125 \text{ km s}^{-1}$ (see contributions by Ord and Bailes).
- High eccentricities of Be/X-ray binaries (Verbunt & van den Heuvel 1995; but see Pfahl et al. 2002).
- Evolutionary studies of NS binary population (in particular the double NS systems) (e.g., Dewey & Cordes 1987; Fryer & Kalogera 1997; Fryer et al. 1998).

(3) Observations of SNe and SNRs: There are many direct observations of nearby SNe (e.g., spectropolarimetry: Wang et al. 2000, Leonard et al. 2001; X-ray and gamma-ray observations and emission line profiles of SN1987A) and SNRs (e.g., Aschenbach et al. 1995; Hwang et al. 2002) which support the notion that SN explosions are not spherically symmetric.

3. NS Kick Mechanisms

Now we review three different classes of mechanisms for generating NS kicks.

Hydrodynamically Driven Kicks

The first class of kick mechanisms relies on hydrodynamics. Since the collapsed core and its surrounding mantle are susceptible to a variety of hydrodynamical (convective) instabilities, one might 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 these local, post-collapse instabilities are not adequate to account for kick velocities $\gtrsim 50 \text{ km s}^{-1}$. To produce
sufficient kicks, the key is to have global asymmetric perturbations in presupernova cores before collapse.

One possible origin for the pre-SN asymmetry is the overstable oscillations in the pre-SN core (Goldreich et al. 1996). The idea is the following. A few hours prior to core collapse, the central region of the progenitor star consists of a Fe core surrounded by Si-O burning shells and other layers of envelope. This configuration is overstable to nonspherical oscillation modes. 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. There are also damping mechanisms for these modes, the most important one being leakage of mode energy: 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. In another word, the g-mode is not exactly trapped in the core. Our calculations (based on the $15 M_\odot$ and $25 M_\odot$ presupernova models of Weaver & Woosley) 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 (see Lai 2001). The typical mode periods are $\gtrsim 1$ s, the growth time $\sim 10 \sim 50$ s, and the lifetime of the Si shell burning is $\sim$ hours. Thus there could be a lot of e-foldings for the nonspherical g-modes to grow. Our preliminary calculations based on the recent models of A. Heger and S. Woosley (Heger et al. 2001) give similar results (work in progress). Our tentative conclusion is that overstable g-modes can potentially grow to large amplitudes prior to core implosion, although several issues remain to be understood better. For example, the O-Si burning shell is highly convective, with convective speed reaching 1/4 of the sound speed, and hydrodynamical simulation may be needed to properly modeled such convection zones (see Bazan & Arnett 1998, Asida & Arnett 2000).

So now we have a way of generating initial asymmetric perturbations before core collapse. During the collapse, the asymmetries are amplified by a factor of 5-10 (Lai & Goldreich 2000). How do we get the kick? The numerical simulations by Burrows & Hayes (1996) illustrate the effect. Suppose the right-hand-side of the collapsing core is denser than the left-hand side. As the shock wave comes out after bounce, it will see different densities in different directions, and it will move preferentially on the direction where the density is lower. So we have an asymmetric shock propagation and mass ejection, a “mass rocket”. The magnitude of kick velocity is proportional to the degree of initial asymmetry in the imploding core.

**Neutrino – Magnetic Field 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$^{-1}$, NS mass $M = 1.4 M_\odot$ and total neutrino energy radiated $E_{\text{tot}} = 3 \times 10^{53}$ erg). There are several possible effects:
(1) 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-NS. Calculations indicate that to generate interesting kicks with this effect requires the proto-NS to have a large-scale, ordered magnetic field of at least a few $10^{15}$ G (see Arras & Lai 1999 and references therein).

(2) Asymmetric Field Topology: Another effect relies on the asymmetric magnetic field distribution in proto-NSs: Since the cross section for $\nu_e (\bar{\nu}_e)$ absorption on neutrons (protons) depends on the local magnetic field strength, the local neutrino fluxes emerged from different regions of the stellar surface are different. Calculations indicate that to generate a kick velocity of $\sim 300$ km s$^{-1}$ using this effect alone would require that the difference in the field strengths at the two opposite poles of the star be at least $10^{16}$ G (see Lai & Qian 1998). Note that only the magnitude of the field matters here.

(3) Dynamical Effect of Magnetic Fields: A superstrong magnetic field may also play a dynamical role in the proto-NS. For example, it has been suggested that a locally strong magnetic field can induce “dark spots” (where the neutrino flux is lower than average) on the stellar surface by suppressing neutrino-driven convection (Duncan & Thompson 1992). While it is difficult to quantify the kick velocity resulting from an asymmetric distribution of dark spots, order-of-magnitude estimate indicates that a local magnetic field of at least $10^{15}$ G is needed for this effect to be of importance.

Electromagnetically Driven Kicks

Harrison & Tademaru (1975) show that electromagnetic (EM) radiation from an off-centered rotating magnetic dipole imparts a kick to the pulsar along its spin axis. The kick is attained on the initial spindown timescale of the pulsar (i.e., this really is a gradual acceleration), and comes at the expense of the spin kinetic energy. A reexamination of this effect (Lai et al. 2001) showed that the force on the pulsar due to asymmetric EM radiation is larger than the original Harrison & Tademaru expression by a factor of four. Nevertheless, to generate interesting kicks using this mechanism requires the initial spin of the NS to be less than $1 - 2$ ms. Gravitational radiation may also affect the net velocity boost.

4. Astrophysical Constraints on Kick Mechanisms

The review in §3 clearly shows that NS kick is not only a matter of curiosity, it is intimately connected to the other fundamental parameters of young NSs (initial spin and magnetic field), and is an important ingredient of SN astrophysics.

One of the reasons that it has been difficult to pin down the kick mechanisms is the lack of correlation between NS velocity and the other properties of NSs. The situation may have changed with the recent X-ray observations of the compact X-ray nebulae of the Crab and Vela pulsars, which have a two sided asymmetric jet at a position angle coinciding with the position angle of the pulsar’s proper motion (Pavlov et al. 2000; Helfand et al. 2001). The symmetric morphology of the nebula with respect to the jet direction strongly suggests that the jet is along the pulsar’s spin axis. Analysis of the polarization angle of Vela’s radio emission corroborates this interpretation (Lai et al. 2001). Thus,
while statistical analysis of pulsar population neither support nor rule out any spin-kick correlation, at least for the Vela and Crab pulsars, the proper motion and the spin axis appear to be aligned.

The apparent alignment between the spin axis and proper motion raises an interesting question: Under what conditions is the spin-kick alignment expected for different kick mechanisms? Let us look at the three classes of mechanisms discussed before (Lai et al. 2001): (1) For the electromagnetically driven kicks, the spin-kick alignment is naturally produced. (Again, note that $P_i \sim 1 - 2$ ms is required to generate sufficiently large $V_{kick}$). (2) For the neutrino–magnetic field driven kicks: The kick is imparted to the NS near the neutrinosphere (at 10's of km) on the neutrino diffusion time, $\tau_{kick} \sim 10$ seconds. As long as the initial spin period $P_i$ is much less than a few seconds, spin-kick alignment is naturally expected. (3) For the hydrodynamically driven kicks: because the kick is imparted at a large radius ($\sim 100$ km), to get effective rotational averaging, we require that the rotation period at $\sim 100$ km to be shorter than the kick timescale ($\sim 100$ ms). This translates to $P_{NS} \lesssim 1$ ms, which means that rotation must be dynamically important.

Currently we do not know whether spin-kick alignment is a generic feature of all pulsars; if it is, then it can provide powerful constraint on the kick mechanisms and the SN explosion mechanisms in general.

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