PULSAR JETS: IMPLICATIONS FOR NEUTRON STAR KICKS AND INITIAL SPINS

DONG LAI, DAVID F. CHERNOFF, AND JAMES M. CORDES

Center for Radiophysics and Space Research, Department of Astronomy, Cornell University, Ithaca, NY 14853; dong@spacenet.tn.cornell.edu, chernoff@spacenet.tn.cornell.edu, cordes@spacenet.tn.cornell.edu

Received 2000 July 18; accepted 2000 November 10

ABSTRACT

We study implications for the apparent alignment of the spin axes, proper motion directions, and polarization vectors of the Crab and Vela pulsars. The spin axes are deduced from recent Chandra X-Ray Observatory images that reveal jets and nebular structure having definite symmetry axes. The alignments indicate that these pulsars were born either in isolation or with negligible velocity contributions from binary motions. We examine the effects of rotation and the conditions under which spin-kick alignment is produced for theoretical models of neutron star kicks. If the kick is generated promptly during the formation of the neutron star by asymmetric mass ejection and/or neutrino emission, then the alignment requires that the proto-neutron star possess, by virtue of the precollapse stellar core's spin, an original spin with period $P_r$ much less than the kick timescale $t_{\text{kick}}$ thus spin averaging the kick forces on the star. The kick timescale ranges from 100 ms to 10 s depending on whether the kick is hydrodynamically driven or neutrino-magnetic field driven. For hydrodynamical models, spin-kick alignment further requires the rotation period of an asymmetry pattern at the radius near shock breakout ($\gtrsim 100$ km) to be much less than $t_{\text{kick}} \lesssim 100$ ms; this is difficult to satisfy unless rotation plays a dynamically important role in the core collapse and explosion (corresponding to $P_r \lesssim 1$ ms). Aligned kick and spin vectors are inherent to the slow process of asymmetric electromagnetic radiation from an off-centered magnetic dipole. We reassess the viability of this electromagnetic rocket effect, correcting a factor of 4 error in Harrison and Tademaru's calculation that increases the size of the effect. To produce a kick velocity of order a few hundred kilometers per second requires that the neutron star be born with $P_r \sim 1$ ms and that spin-down due to $r$-mode-driven gravitational radiation be inefficient compared to standard magnetic braking. The electromagnetic rocket operates on a timescale of order $0.3 (B/10^{13} \text{ G})^{-2}$ yr. The apparent spin-kick alignment in the Crab and Vela pulsars places important new constraints on each of the mechanisms of neutron star kicks that we consider.

Subject headings: pulsars: individual (PSR B0531+21, PSR B0833-45) — stars: neutron — stars: rotation — supernovae: general

1. INTRODUCTION

It has long been recognized that neutron stars have space velocities much greater than those of their progenitors. Recent studies of pulsar proper motion give 200–500 km s$^{-1}$ as the mean three-dimensional velocity of neutron stars at birth (e.g., Lyne & Lorimer 1994; Lorimer, Bailes, & Harrison 1997; Hansen & Phinney 1997; Cordes & Chernoff 1998), with a significant population having velocities greater than 1000 km s$^{-1}$. Direct evidence for pulsar velocities $\gtrsim 1000$ km s$^{-1}$ comes from observations of the bow shock produced by the Guitar Nebula pulsar (B2224+65) in the interstellar medium (Cordes, Romani, & Lundgren 1993). A natural explanation for such high velocities is that supernova explosions are asymmetric and provide kicks to nascent neutron stars. The geodetic precession in the binary pulsar PSR 1913+16 (Weisberg, Romani, & Taylor 1989; Cordes, Wasserman, & Blaskiewicz 1990; Kramer 1998; Wex, Kalogera, & Kramer 2000), the orbital plane precession in the PSR J0045–7319/B-star binary and its fast orbital decay (Kaspi et al. 1996; Lai, Bildsten, & Kaspi 1995; Lai 1996), and the high eccentricities of Be/X-ray binaries (see van den Heuvel & van Paradijs 1997) all support the notion of neutron star kicks. The recently detected high systemic velocity ($\approx 430$ km s$^{-1}$) of the X-ray binary Circinus X-1 (Johnston, Fender, & Wu 1999) can only be produced by a neutron star kick of at least $\sim 500$ km s$^{-1}$ (Tauris et al. 1999). Evolutionary studies of neutron star binary populations also imply the existence of pulsar kicks (e.g., Dewey & Cordes 1987; Fryer & Kalogera 1997; Fryer, Burrows, & Benz 1998). Finally, there are many direct observations of nearby supernovae (e.g., Wang et al. 2001) and supernova remnants which show that supernova explosions are not spherically symmetric.

While the evidence for such kicks is unequivocal, the physical origin remains unclear. A natal kick could be generated by an asymmetric explosion due to global hydrodynamical perturbations in the supernova core (Goldreich, Lai, & Sari 1996; Burrows & Hayes 1996; Lai 2000a; Lai & Goldreich 2000; D. Lai & P. Goldreich 2001, in preparation), or it could be a result of asymmetric neutrino emission in the presence of superstrong magnetic fields ($B \gtrsim 10^{13}$ G) in the proto–neutron star (e.g., Lai & Qian 1998; Arras & Lai 1999a, 1999b, and references therein). A postnatal kick mechanism studied by Harrison & Tademaru (1975) relies on asymmetric electromagnetic radiation from an off-centered dipole in a rapidly rotating pulsar. All these possibilities have intrinsic uncertainties (see §§ 3 and 4 below). Part of the reason that it is difficult to determine which mechanism is at work is the lack of any simple relationship between velocity and other properties of neutron stars (but see § 2). For example, despite some early claims, statistically there is no evidence for a correlation between velocity and magnetic moment for radio pulsars (Lorimer et al. 1997; Cordes & Chernoff 1998) or between velocity and rotation (Deshpande, Ramachandran, & Radhakrishnan 1999). Unfortunately, given the large systematic
uncertainties, these statistical results, by themselves, cannot be used to support or rule out particular kick mechanisms (see § 2.3).

Recent observations of the Vela pulsar and the surrounding compact X-ray nebula with the Chandra X-Ray Observatory reveal 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, Gotthelf, & Halpern 2001).\(^1\) The symmetric morphology of the nebula with respect to the jet direction strongly suggests that the jet is along the pulsar's spin axis. In § 2.1 we examine the polarization angle of Vela's radio emission, which corroborates this interpretation. Evidence for spin-velocity alignment also exists for the Crab pulsar (§ 2.2). We argue in § 2.3 that current observations of other pulsars neither support nor rule out any spin-kick correlation.

The alignment between the projected spin axis and proper motion (for Vela and Crab) immediately demonstrates that binary breakup along with symmetric supernova explosions (see Iben & Tutukov 1996) is not likely to be responsible for the observed proper motion. Binary disruption would yield orthogonal spin and velocity vectors if pre-explosion binaries have aligned spin and orbital angular momenta (e.g., by virtue of tidal coupling) and if the neutron star's spin is in the same direction as the progenitor's. Projection onto the plane of the sky could fortuitously yield apparently parallel spin and velocity vectors, of course, but this is a low-probability occurrence. The observed spin-velocity alignment in the Vela and Crab pulsars, then, indicates that the pulsar was born in isolation or the progenitor binary was so wide that the orbital speed was negligible compared to the kick. In §§ 3 and 4 below, we ignore the binary possibility and examine how rotation may affect kick and under what conditions spin-kick alignment is expected for different kick mechanisms.

2. OBSERVATIONAL CONSTRAINTS ON THE GEOMETRY OF PULSAR SPIN AND VELOCITY

Here we briefly discuss observational results related to spin–proper motion correlation in pulsars.

2.1. Vela Pulsar

The proper motion of the Vela pulsar \((\mu_\alpha, \mu_\delta) = (-48 \pm 2, 35 \pm 1)\) mas yr\(^{-1}\) (Bailes et al. 1990) is at position angle \(\psi_\mu = -53.9 \pm 1.4^\circ\) and implies a two-dimensional velocity \(D\mu \approx 70-141\) km s\(^{-1}\) for a distance \(D = 0.25-0.5\) kpc. The proximity of the pulsar to the Earth implies that any correction for differential galactic rotation is small. The X-ray jet and bow shock axes of the pulsar nebula lie in the same direction as the proper motion to within 5° (Pavlov et al. 2000). If the jet originates from the pulsar magnetosphere, as seems likely, it is most natural to associate the jet axis with the pulsar spin axis.

Another constraint on the geometry comes from radio polarization. The Vela pulsar formed the basis for the rotating vector model (Radhakrishnan & Cooke 1969), which relates the polarization position angle to the rotating dipolar magnetic field of the neutron star. At the pulse centroid, the spin axis, magnetic moment, and line of sight are coplanar. Because the radiation is highly beamed, the polarization angle at the pulse center is determined by the orientations of the stellar magnetic field and of the projected spin axis. Phenomenologically, radio emission often conforms to this picture, but the polarization angle can be in one of two orientations separated by 90°. Among various pulsars, the two modes vary stochastically from pulse to pulse as well as systematically across pulse phase. In some objects, the emission seems to be dominated by one mode in all pulses and at all pulse phases.

Using data from Deshpande et al. (1999), which have been corrected for Faraday rotation in the interstellar medium and in the ionosphere, the pulse centroid polarization angle is \(\psi_{pol} = 35° \pm 10°\). The difference angle between the proper motion and polarization angle is \(\Delta\psi = \psi_{pol} - \psi_p = 89° \pm 11°\), i.e., the polarization vector is perpendicular to the proper motion axis.

We conclude that the space velocity and X-ray jet axes are parallel in projection on the plane of the sky. Moreover, the radio polarization angle is 90° with respect to this axis, implying that the polarization mode dominant in the Vela pulsar is one where the electric field in radio emission is orthogonal to the magnetospheric field.

The a priori chance of alignment (or antialignment) of three direction vectors (corresponding to proper motion, perpendicular polarization, and X-ray jet axes) is small. We assume each is uniformly distributed on a sphere and use measurement uncertainties of 1°, 4°, and 5°, respectively, to infer a probability of 0.6%. The corresponding probability increases to 1.2% if alignment of either the parallel or the perpendicular polarizations is considered.

2.2. Crab Pulsar

Caraveo & Mignani (1999) report a new Hubble Space Telescope–derived proper motion for the Crab pulsar, \((\mu_\alpha, \mu_\delta) = (-17 \pm 3, 7 \pm 3)\) mas yr\(^{-1}\), or \(\mu = 18 \pm 3\) mas yr\(^{-1}\) with a position angle \(\psi_\mu = 292° \pm 10°\), corresponding to a transverse velocity of 171 km s\(^{-1}\) for \(D = 2\) kpc. Their results are consistent with those reported by Wyckoff & Murray (1977) using historical images of the Crab Nebula. Though \(~2\) kpc away, differential galactic rotation is negligible because the pulsar is within 5° of the Galactic anticenter direction. Caraveo & Mignani pointed out that the proper motion and the symmetry axis of the inner X-ray nebula, based on ROSAT images, were essentially parallel. Arguing that the X-ray structure's symmetry is determined by the pulsar's spin axis, they suggested that the (projected) spin axis and proper motion are parallel. The recent Chandra X-ray image (see Weisskopf et al. 1999)\(^2\) confirms this picture, which is also consistent with the optical work of Hester et al. (1995). While the morphology of the X-ray emission is less structured and less symmetric than the Vela pulsar's nebula, there is a well-defined axis that indeed is parallel with the proper motion to within the errors.

Interpretation of the Crab pulsar's polarization is less clear than that of Vela, primarily because there is a multiplicity of components whose relationship to the spin axis is ambiguous. However, radio polarization at 1.4 GHz (Moffett & Hankins 1999) has position angle (after correction for Faraday rotation) \(\psi_{pol} \approx -60° \pm 10°\) for both the main pulse (MP) and interpulse (IP) components. At 5 GHz, the polarization angle for the MP is the same while the IP

---

\(^1\) Image available at http://chandra.harvard.edu/photo/cycle1/vela.

\(^2\) Image available at http://chandra.harvard.edu/photo/0052.
angle is shifted by 90° to 30° ± 10°. At 8 GHz, the MP is not visible, while the IP has the same position angle as at 5 GHz. Two new radio components (HFC1, HFC2) appear at 8 GHz that arrive later than the IP and have position angles ~85° ± 15°. At frequencies less than 1 GHz, a “precursor” component appears before the MP, but its polarization angle is not available. At optical and UV wavelengths (Graham-Smith et al. 1988, 1996), the polarization angles at the centroids of the MP and IP are the same as in the radio (modulo 90° polarization-mode ambiguities).

Empirically, the polarization vector at the centroid of the MP is parallel to the proper motion vector. The simplest interpretation is that the polarization mode in this pulse component is parallel to the projected spin axis. However, alternative models exist for the Crab pulsar’s emission that place the emission region at sufficiently high altitude (in “outer gap” models) that rotational aberration would break the coplanarity of the line-of-sight, spin, and magnetic dipole vectors (e.g., Romani & Yadigaroglu 1995). The geometry of the Crab’s X-ray nebula may help clarify the emission geometry.

2.3. The Neutron Star–Neutron Star Binary B1913 +16

Analysis of the orbital elements, proper motion, and limits on the geodetic precession angle leads to the conclusion that a kick resulted from the most recent supernova that produced the observed pulsar’s companion and constrains the angle between the kick and orbital plane (Wex et al. 2000). The angle is less than 5°–10° when the following hold: (1) all angular momenta (spin and orbital) were aligned prior to the explosion (consistent with the canonical evolutionary history of double–neutron star systems), (2) the kick timescale was much shorter than the orbital period (currently ~8 hr), and (3) the orbit did not evolve significantly since the explosion (see Fryer & Kalogera 1997). If the current determination of the hard-to-measure geodetic angle is ignored, then the angle between kick and orbital plane is limited to less than 30° primarily by the condition that the binary remain bound.

For all such analyses, the following is important: the axis of the spin of the most recently formed neutron star is unobserved, so the spin-kick orientation can be inferred only if one also assumes that the neutron star spin was aligned with the progenitor’s spin. Although plausible, there is no proof that the spin direction of the iron core of this neutron star progenitor matched the presupernova orbital angular momentum. We conclude that the results for B1913 +16 do not demand a different sort of kick mechanism than for the Crab and Vela pulsars. At the same time, if spin-kick alignment holds for B1913 +16, if the angle between kick and orbital plane is less than 30°, and if all angular momenta align, then the spin of the most recently formed neutron star in that system is misaligned with the spin of the progenitor.

2.4. Other Pulsars

The alignments of proper motion vectors and projected spin axes for the Vela and Crab pulsars may be contrasted with what we know about other pulsars’ geometries. For other pulsars, we have no information about the orientation of the spin axis from nebular morphology. All that is known is based on radio polarization. For the 28 pulsars (besides Vela) analyzed by Deshpande et al. (1999), there appears to be no systematic relationship between the polarization and proper motion vectors. We have used a likelihood analysis to compare different model relationships between these vectors. The null hypothesis that they are independently and uniformly distributed on the sphere was compared with two competing hypotheses: (1) that there is perfect correlation between the spin axis and either one polarization mode or its orthogonal counterpart; (2) a hybrid model where some objects have uncorrelated angles and others have perfectly correlated angles, modulo the 90° ambiguity. The likelihood analysis indicates, formally, that the best model is one where 80% of the objects have uncorrelated angles while 20% have deterministically related angles. However, the likelihood for this model is not significantly better than the null hypothesis. For the population of objects, we conclude, therefore, that there is no strong relationship between the polarization angle and the orientation of the proper motion.

The lack of any empirically establishable correlation for a sample of pulsars should not be viewed as evidence that kicks and spins are usually unrelated. At least four effects can contaminate a potential correlation: (1) As discussed in §2.1, there are large uncertainties in using the polarization angle to determine the spin axis; while the rotating vector model works well in fitting polarization angles versus pulse phase in many cases, in others it does not. Also, aberration introduces an angular shift that depends on emission altitude, which may vary from object to object (Blaskiewicz, Cordes, & Wasserman 1991). “Orthogonal” polarization modes for some objects are not always precisely orthogonal, raising the question of whether the inference of the orientation of the spin axis from the polarization may be biased from the true value in some cases. About half the objects in Deshpande et al.’s sample are said to be affected by orthogonal mode flips. (2) Most neutron stars may be formed in binary systems, and in such cases their present space velocities are a combination of disrupted orbital motion and one or two kick velocities. Any spin axis–kick velocity relationship can be diminished through this combination. While it is true that some pulsars have sufficiently large space velocities that any orbital contribution would be small, it is also true that other objects have sufficiently small space velocities that orbital motion may have contributed significantly. (3) Differential galactic rotation is important for distant objects and cannot be accounted for unless the distance is known accurately and the object has not moved far from its birth location. Seven objects in the Deshpande et al. sample have estimated distances greater than 3 kpc, and it is possible that others originated far enough away to be so affected. (4) The spin velocity angle can be altered by acceleration in the Galactic potential for objects older than about 10 Myr. Five objects in the sample exceed this age.

We stress that Deshpande et al. (1999) were careful to select objects whose polarization angle sweeps appeared to match the shape expected from the rotating vector model. However, that model has sufficient parameters to fit any smooth position angle curve even if that curve does not derive from the physical conditions that underlie that model. A cogent example is, once again, the neutron star–neutron star binary B1913 +16. At 1.4 GHz, its pulse shape is dominated by two components that can be associated with a “conal” beam; the position angle curve indeed appears to follow a curve similar to that expected from the rotating vector model at the pulse phases of these components. However, there is also contribution to the pulse from a “core” component, as evidenced by its appearance.
at lower frequencies. In the 1.4 GHz polarization data, the position angle curve deviates markedly from the rotating vector model at pulse phases corresponding to the core component (Cordes et al. 1990). This raises the suspicion that the polarization angle sweep of core components does not map the projection of the (assumed) dipolar field lines and thus does not allow determination of the orientation of the spin axis. Given that core component emission probably arises at or near the surface of the neutron star (e.g., Rankin 1990), it is plausible that the magnetic field is distorted from a dipolar form there. Several objects in Deterspande et al.'s sample have profiles dominated by core components, and several others show core components combined with conal emission.

In summary, statistical studies do not allow one to conclude that the angle between spin axes and kick directions is uniformly distributed on the sky. The Crab and Vela pulsars are not affected by these uncertainties because the Chandra X-ray data give an independent orientation vector that is presumed to coincide with their spin axes.

3. IMPLICATIONS FOR KICK MECHANISMS: NATAL KICKS

Recent studies have focused on natal kicks imparted to the neutron star at birth. The strongest observational evidence that kicks must be natal comes from spin-orbit misalignment in the binary pulsar systems PSR J0045−7319 (Kaspi et al. 1996) and PSR 1913+16 (Kramer 1998) needed to produce the observed precessions. The alternative, postnatal electromagnetic rocket mechanism (Harrison & Tademaru 1975) will be discussed in § 4. We discuss below the implications of aligned spin–kick in two classes of natal kick mechanisms: hydrodynamically driven and neutrino–magnetic field driven.

3.1. Hydrodynamically Driven Kicks

The first class relies on hydrodynamical perturbations in core collapse and supernova explosions. Numerical simulations indicate that local hydrodynamical (convective) instabilities in the collapsed stellar core and its surrounding shocked mantle (e.g., Herant et al. 1994; Burrows, Hayes, & Fryxell 1995; Janka & Müller 1994, 1996; Keil, Janka, & Müller 1996; Mezzacappa et al. 1998), which might in principle lead to asymmetric matter ejection and/or asymmetric neutrino emission, are not adequate to account for kick velocities $\gtrsim 100$ km s$^{-1}$ (Janka & Müller 1994; Burrows & Hayes 1996; Keil 1998). Global asymmetric perturbations of presupernova cores are required to produce the observed kicks hydrodynamically (Goldreich et al. 1996; Burrows & Hayes 1996). Goldreich et al. (1996) suggested that overstable g-mode oscillations in the presupernova core driven by shell nuclear burning may provide a natural seed for the initial asymmetry. Calculations based on presupernova models of Weaver & Woosley (1993) indicate that some g-modes are indeed overstable (D. Lai & P. Goldreich 2001, in preparation; see Lai 2000a), although uncertainties in the presupernova models preclude a definitive prediction of the perturbation amplitudes. Alternatively, violent convection in the O–Si burning shell may also produce asymmetric perturbations (Bazan & Arnett 1998), although it is not clear whether such perturbations have sufficiently large scales. During collapse, the asymmetric perturbations seeded in the outer region of the iron core are amplified (by a factor of 5–10) by gravity (Lai & Goldreich 2000). The enhanced asymmetric density perturbation leads to asymmetric shock propagation and breakout, which then gives rise to asymmetry in the explosion and a kick velocity to the neutron star (Burrows & Hayes 1996).

Now let us consider how rotation might affect the kick. The low-order g-modes trapped in the presupernova core ($M \approx 1.4 M_\odot$, $R \approx 1500$ km) have periods of 1–2 s, much shorter than the rotation period of the core; thus the g-modes are not affected by rotation. Also, since the rotational speed of the core is typically less than the speed of convective eddies ($\approx 1000$–2000 km s$^{-1}$, about 20% of the sound speed) in the burning shell surrounding the iron core, rotation should not significantly affect the shell convection either. (The convection zone provides an evanescent region for trapping the g-modes). Under these conditions, the development of large-scale presupernova (dipolar) asymmetry is not influenced by the core rotation.

Even though the primary thrust to the neutron star (upon core collapse) does not depend on spin, the net kick will be affected by rotational averaging if the asymmetry pattern (near the shock breakout) rotates with the matter at period $P$ shorter than the kick timescale $\tau_{kick}$. Let $V_0$ be the kick velocity that the neutron star attains in the case of zero rotation, and let $\theta$ be the angle between the primary asymmetry and the rotation axis. The expected components of kick along the rotation axis and perpendicular to it are (for $\tau_{kick} \gg P$)

$$V_{kick||} = V_0 \cos \theta, \quad V_{kick\perp} \sim \frac{\sqrt{2P}}{2\pi \tau_{kick}} V_0 \sin \theta. \quad (1)$$

Thus, the angle $\beta$ between the kick vector $V_{kick}$ and the spin vector $\Omega_s$ is given by $\tan \beta \sim 0.2(P/\tau_{kick}) \tan \theta$. Typically, the alignment between $V_{kick}$ and $\Omega_s$ will be achieved when $\tau_{kick} \gg P$.

What is the kick timescale $\tau_{kick}$? In the standard paradigm of core collapse supernovae, the shock wave generated by core bounce starts at a radius of $\sim 20$ km (which encloses $0.7 M_\odot$), reaches 100–200 km in about 20 ms and stalls for hundreds of milliseconds until it is revived by neutrino heating (perhaps enhanced by vigorous convection in the mantle), and then moves outward again. As the shock breaks out asymmetrically, momentum is imparted to the matter that will be incorporated into the neutron star on a timescale somewhat shorter than the delay. A reasonable estimate is $\tau_{kick} \sim 100$ ms, which is the shock travel time at speed of $10^4$ km s$^{-1}$ across $\sim 1000$ km, the radius of the mass cut enclosing 1.4 $M_\odot$ (e.g., Bethe 1997; Burrows & Hayes 1996). For spin–kick alignment, the rotational period of the perturbation pattern at $r = 100 r_s$ km must be much less than $\tau_{kick}$. This corresponds to a final neutron star ($R = 10$ km) spin period $P_s \ll \tau_{kick}/100 r_s^2 \sim 1 r_s^{-2}$ ms. Note

3 Perturbations in the inner core (which collapses homologously) are damped during collapse (Lai 2000b); thus the proto–neutron star is globally spherical.

4 The minimum rotation period of an isolated (i.e., decoupled from the envelope) core is about 1 s, and a real core must rotate significantly slower than this due to core-envelope coupling. Note that even if the newly formed neutron star rotates at the maximum breakup rate ($P_s \approx 0.5$ ms), the corresponding rotation period of the precollapse core is only $\sim 11$ s.

5 For example, the density-temperature structure of the rotating presupernova stellar model of Heger, Langer, & Woosley (2000), which does not include magnetic core–envelope coupling and thus overestimates the rotational effect, is not much different from the nonrotating model.
that since the shock wave travels from ~100 to ~1000 km while the kick is being imparted to the star (e.g., Burrows & Hayes 1996), \( r_k = 1 \) corresponds to the maximum spin period of the final neutron star. We thus conclude that if rotation is dynamically unimportant for the core collapse and explosion (corresponding to \( P_1 \gg 1 \) ms), then rotational averaging is inefficient and the hydrodynamical mechanism does not produce spin-kick alignment.6

The discussion above is based on the standard picture of core collapse supernovae, which is valid as long as rotation does not play a dynamically important role (other than rotational averaging) in the supernova. If, on the other hand, rotation is dynamically important, the basic collapse and explosion may be qualitatively different (e.g., core bounce may occur at subnuclear density, the explosion is weaker and takes the form of two-sided jets; Mönchmeyer et al. 1991; Rampp, Müller, & Ruffert 1998; Khokhlov et al. 1999; Fryer & Heger 2000). The possibility of a kick in such systems has not been studied, but it is conceivable that an asymmetric dipolar perturbation may be coupled to rotation, thus producing spin-kick alignment.

### 3.2. Neutrino–Magnetic Field Driven Kicks

The second class of kick mechanisms relies on asymmetric neutrino emission induced by strong magnetic fields.7 The fractional asymmetry \( \epsilon \) in the radiated neutrino energy required to generate a kick velocity \( V_{\text{kick}} \) is \( \epsilon = MV_{\text{kick}}/E_{\text{tot}} = 0.028 \) for \( V_{\text{kick}} = 1000 \text{ km s}^{-1} \), \( M = 1.4 M_\odot \), and total neutrino energy \( E_{\text{tot}} = 3 \times 10^{53} \text{ ergs} \). In the magnetized neutron medium, the neutrino scattering/absorption opacities depend asymmetrically on the directions of neutrino momenta with respect to the magnetic field axis. (This is a manifestation of parity violation in weak interactions.) 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 from thermal equilibrium (Vilenkin 1995; Arras & Lai 1999a, 1999b). Arras & Lai (1999a, 1999b) found that, averaging over all neutrino species, the total asymmetry in neutrino flux is \( \epsilon \sim 0.1B_{15}E_6^{-1} + 0.002B_{15}/T \) (the first term comes from the effect of quantized states of electrons in the absorption opacity, and the second term comes from nucleon polarization), where \( B = 10^{15}B_{15} \) G is the magnetic field strength, \( E_6 \) is the mean energy (in MeV) of \( \nu_s \), and \( T \) is the temperature (in MeV) in the decoupling layer. The resulting kick velocity is \( V_{\text{kick}} \sim 50B_{15} \text{ km s}^{-1} \). Kicks of a few hundred kilometers per second would require the proto-neutron star to possess an ordered component of magnetic field with magnitude greater than \( 10^{15} \) G. Alternatively, since the cross section for \( \nu_s \) absorption on neutrons (protons) depends on the local magnetic field strength, asymmetric neutrino emission can be produced if the field strengths at the two opposite stellar poles be at least \( 10^{16} \) G (Lai & Qian 1998).

A superstrong magnetic field may also play a dynamical role in the proto–neutron star. For example, it has been suggested that the magnetic field can induce “dark spots” (where the neutrino flux is lower than average) on the stellar surface by suppressing neutrino-driven convection (Thompson & Duncan 1993). While it is difficult to quantify the kick velocity resulting from an asymmetric distribution of dark spots, a simple estimate indicates that a local magnetic field of at least \( 10^{15} \) G is needed for this effect to be of importance.

In this second class of mechanisms, the kick is imparted to the neutron star near the neutrinosphere on the neutron diffusion time, \( \tau_{\text{kick}} \sim 10 \) s. As long as the initial rotation period of the neutron star is much less than a few seconds, spin-kick alignment is naturally expected (see eq. [1]). Of course, while soft gamma repeaters and anomalous X-ray pulsars may possess magnetic fields in excess of \( 10^{14} \) G (“magnetars”; e.g., Thompson & Duncan 1996; Vasisht & Gotthelf 1997; Kouveliotou et al. 1998, 1999), it is unclear (and perhaps unlikely) that radio pulsars (and Vela and Crab in particular) had \( B > 10^{15} \) G at birth for these neutrino–magnetic field driven kicks to be relevant.

### 3.3. Kick-Induced Spin?

For the two classes of kick mechanisms discussed in § 3.1 and § 3.2, spin-kick alignment requires that the proto-neutron star have a “primordial” rotation (i.e., with angular momentum coming from the presupernova core and possibly at a maximum rate if the kick is generated hydrodynamically). How about the notion that the pulsar’s spin is generated by off-centered kicks (Spruit & Phinney 1998)? Is it certainly true that even with zero precollapse angular momentum, some rotation can be produced in the proto-neutron star (Burrows et al. 1995 reported a rotation period of order 1 s generated by stochastic torques in their two-dimensional simulations of supernova explosions): a kick \( V_{\text{kick}} = 300V_{\text{300}} \text{ km s}^{-1} \), displaced by a distance \( \delta \) from the center, produces a spin \( \Delta \Omega = 12\Omega_{\text{300}}(5/10) \text{ Hz} \), with the spin axis necessarily perpendicular to the kick direction (Burrows et al. 1995; Spruit & Phinney 1998). Aligned spin-kicks may be possible if the kick is the result of many small thrusts that are appropriately oriented (Spruit & Phinney 1998)—such a picture might apply if small-scale convection were responsible for the kick. However, numerical simulations indicate that such convection alone does not produce kicks of sufficient amplitude (Janka & Müller 1994; Burrows & Hayes 1996; Keil 1998). As discussed in §§ 3.1 and 3.2, kicks of a few hundred kilometers per second can be generated if global dipolar symmetry is broken (either due to hydrodynamical perturbations or due to magnetic fields).

### 4. POSTNATAL KICK: ELECTROMAGNETIC ROCKET EFFECT

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 spin-down timescale of the neutron star (Keil 1998).
pulsar (i.e., this really is a gradual acceleration), and comes at the expense of the spin kinetic energy. We have reexamined this effect and found that the force on the pulsar due to asymmetric EM radiation is larger than the original Harrison & Tademaru expression by a factor of 4. If the dipole is displaced by a distance \( s \) from the rotation axis and has components \( \mu_\rho, \mu_\phi, \mu_z \) (in cylindrical coordinates), the force is given by (to leading order in \( \Omega s/c \))

\[
F = \frac{8}{15} \left( \frac{\Omega^2}{c} \right) \Omega^2 \mu_\rho \frac{c^2}{\rho^4},
\]

(2)

(The sign is such that negative \( F \) implies \( V_{\text{kick}} \) parallel to the spin \( \Omega \).) The dominant terms for the spin-down luminosity give

\[
L = \frac{20\Omega^4}{3c^3} \left( \mu_\rho^2 + \mu_\phi^2 + \frac{2\Omega^2 \mu_z^2}{5c^2} \right).
\]

(3)

For a "typical" situation, \( \mu_\rho \sim \mu_\phi \sim \mu_z \), and the asymmetry parameter \( \epsilon \equiv F/(L/c) \) is of order 0.4(\( \Omega s/c \)). For a given \( \Omega \), the maximum \( \epsilon_{\text{max}} = \sqrt{0.4} = 0.63 \) is achieved for \( \mu_\rho/\mu_\phi = 1 \) and \( \mu_\phi/\mu_z = \sqrt{0.4(\Omega s/c)} \). From \( \dot{M}V = \epsilon(L/c) = -\epsilon(I\Omega)/c \), we obtain the kick velocity

\[
V_{\text{kick}} \approx 260R_1^2 \left( \frac{v_i}{1 \text{ kHz}} \right)^2 \left[ 1 - \left( \frac{v_i}{v_f} \right)^2 \right] \text{ km s}^{-1}
\]

\[
\approx 140R_1^2 \frac{s}{10 \text{ km}} \left( \frac{v_i}{1 \text{ kHz}} \right)^3 \left[ 1 - \left( \frac{v_i}{v_f} \right)^2 \right] \text{ km s}^{-1},
\]

(4)

where \( R = 10R_1 \text{ km} \) is the neutron star radius, \( v_i \) is the initial spin frequency, \( v_f \) is the current spin frequency of the pulsar, and \( \epsilon = (\Omega_i^2 - \Omega^2)^{-1} \). In the second equality, we have adopted the "typical" situation \( \mu_\rho = \mu_\phi = \mu_z \), so that \( \epsilon = 0.4(\Omega s/c) \). For the "optimal" condition, with \( \mu_\rho = 0, \mu_\phi/\mu_z = \sqrt{0.4(\Omega s/c)} \), and \( \epsilon = \sqrt{0.4(2\Omega_i^2/\Omega^2 + \Omega_i^2)} \), we find

\[
V_{\text{kick}}^{(\text{max})} \approx 1400R_1^2 \left( \frac{v_i}{1 \text{ kHz}} \right)^4 \times \left[ 1 - 4.66 \left( \frac{v_f}{v_i} - \tan^{-1} \frac{v_f}{v_i} \right) \right] \text{ km s}^{-1}.
\]

(5)

Thus if the neutron star was born rotating at \( v_i \approx 1 \text{ kHz} \), it is possible, in principle, to generate spin-aligned kick of a few hundred kilometers per second or even 1000 km s\(^{-1}\). Equations (4) and (5) assume that the rotational energy of the pulsar entirely goes to electromagnetic radiation. Recent work has shown that a rapidly rotating \( (v \approx 100 \text{ Hz}) \) neutron star can potentially lose significant angular momentum to gravitational waves generated by unstable \( r \)-mode oscillations (e.g., Andersson 1998; Lindblom, Owen, & Morsink 1998; Owen et al. 1998; Andersson, Kokkotas, & Schutz 1999; Ho & Lai 2000). If gravitational radiation carries away the rotational energy of the neutron star faster than the EM radiation does, then the electromagnetic rocket effect will be much diminished.\(^6\) In the linear regime, the \( r \)-mode amplitude \( x \sim \zeta/R \) (where \( \zeta \) is the surface Lagrangian displacement; see the references cited above for more precise definition of \( x \)) grows due to gravitational radiation reaction on a timescale \( \tau_{\text{grow}} \approx 19(10^{-3} \text{ kHz})^{-6} \text{ s} \). Starting from an initial amplitude \( x_i \ll 1 \), the mode grows to a saturation level \( x_{\text{sat}} \) in time \( \tau_{\text{grow}} \ln(x_{\text{sat}}/x_i) \), during which very little rotational energy is lost. After saturation, the neutron star spins down due to gravitational radiation on a timescale

\[
\tau_{\text{GR}} = \left( \frac{\dot{v}}{\dot{v}_{\text{GR}}} \right) \approx 100x_{\text{sat}}^2 \left( \frac{v}{1 \text{ kHz}} \right)^{-6} \text{ s},
\]

(6)

(Owen et al. 1998). By contrast, the spin-down time due to EM radiation alone is

\[
\tau_{\text{EM}} = \left( \frac{\dot{v}}{\dot{v}_{\text{EM}}} \right) \approx 10^7B_{1.3}^3 \left( \frac{v}{1 \text{ kHz}} \right)^{-2} \text{ s},
\]

(7)

where \( B_{1.3} \) is the surface dipole magnetic field in units of \( 10^{13} \text{ G} \). Including gravitational radiation, the kick velocity becomes

\[
V_{\text{kick}} = \frac{I}{\dot{M}c} \int_{\Omega_i}^{\Omega} \epsilon \frac{\dot{v}_{\text{GR}}}{\dot{v}_{\text{GR}} + \dot{v}_{\text{EM}}} \Omega d\Omega
\]

\[
\approx 260R_1^2 \frac{s}{10 \text{ km}} \left( \frac{v_i}{1 \text{ kHz}} \right)^3 \left[ 1 - \left( \frac{v_i}{v_f} \right)^2 \right] \left[ 1 + \beta \right] \text{ km s}^{-1},
\]

(8)

where in the second equality we have replaced \( \epsilon \) by constant mean value \( \bar{\epsilon} \) and \( \beta \) is defined by

\[
\beta \equiv \frac{\dot{v}_{\text{EM}}}{\dot{v}_{\text{GR}}} \approx \left( \frac{x_{\text{sat}}}{10^{-2.3}} \right) \left( \frac{v_i}{1 \text{ kHz}} \right)^4 B_{1.3}^{-2}.
\]

(9)

For \( \beta \ll 1 \), equation (8) becomes equation (4); for \( \beta \gg 1 \), the kick is reduced by a factor \( 1/\beta \).

Clearly, for the EM rocket to be viable as a kick mechanism at all requires \( \beta \ll 1 \). The value of \( x_{\text{sat}} \) is unknown. Analogy with secularly unstable bar-mode in a Maclaurin spheroid implies that \( x_{\text{sat}} \sim 1 \) is possible. It has been suggested that turbulent dissipation in the boundary layer near the crust (if it exists early in the neutron star’s history) may limit \( x_{\text{sat}} \) to a small value of order \( 10^{-2} - 10^{-3} \) (Wu, Matzner, & Arras 2000). The theoretical situation is not clear at this point.

The EM rocket effect has not been popular in recent years because empirical tests using radio polarization and proper motion have not yielded a positive correlation and because it is widely thought that radio pulsars are born with spin periods of 0.02 – 0.5 s (e.g., Lorimer et al. 1993). However, as discussed in § 2.3, the polarization–proper motion correlation might not be detectable even if kicks are always aligned with spin axes. The recent discovery of the 16 ms X-ray pulsar PSR J0537 – 6910 associated with the Crab-like supernova remnant N157B (Marshall et al. 1998) implies that at least some neutron stars are born with spin periods in the millisecond range. In particular, a recent analysis of the energetics of the Crab Nebula suggests an initial spin period \( \sim 3 - 5 \text{ ms} \) followed by fast spin-down on a timescale of 30 yr (Atoyan 1999). As for the Vela pulsar, the

\(^6\) Gravitational radiation can also carry away linear momentum, but the effect for a neutron star is negligible.
energies of the remnant do not yield an unambiguous constraint on the initial spin (S. Reynolds 2000, private communication). Thus, it seems prudent to consider the EM rocket effect as a possible kick mechanism. We do note, however, that such slow postnatal kick may have difficulty explaining some properties of binary pulsar systems, such as the spin-orbit misalignment in PSR J0045−7319 (Kaspi et al. 1996) and PSR 1913+16 (Kramer 1998) needed to produce the observed precessions.\(^\text{10}\) Similarly, a slow kick (with \(\tau_{\text{kick}} \gtrsim P_{\text{orb}}\)) may be inconsistent with the neutron star binary population, e.g., Dewey & Cordes 1987; Fryer & Kalogera 1997; Fryer et al. 1998). Some of these issues will be addressed in a future paper.

5. CONCLUSION

Motivated by the apparent alignment between the spin axis and the proper motion for the Vela and Crab pulsars as revealed by recent Chandra observations and by analysis of radio polarization (§2), we have examined in this paper the questions of how rotation affects kick and whether spin-kick alignment is generally expected in different classes of theoretical models of neutron star kicks. We find the following:

1. For hydrodynamically driven kicks, spin-kick alignment is possible only if rotation plays a dynamically impor-

\(^\text{10}\) For instance, in the case of the PSR J0045−7319/B-star binary, if we assume that the orbital angular momentum of the presupernova binary is aligned with the spin of the B star, then the current spin-orbit misalignment can only be explained by a fast kick with \(\tau_{\text{kick}}\) less than the postexplosion orbital period \(P_{\text{orb}}\); if we further assume that the iron core of the progenitor of PSR J0045−7319 had a spin aligned with the orbit, then the fast kick must not have been along the neutron star spin axis. See also §2.3 for the case of the BSR B1913+16.

This work is supported in part by NASA grants NAG5-8356 and NAG5-8484, by NSF grants AST 98-19931 and AST 99-86740, and by a research fellowship (to D. L.) from the Alfred P. Sloan Foundation.

REFERENCES

Akhmedov, E. K., Lanza, A., & Sciama, D. W. 1997, Phys. Rev. D, 56, 6117.

Andersson, N., 1998, ApJ, 502, 708.

Andersson, N., Kokkotas, K. D., & Schutz, B. F. 1999, ApJ, 510, 846.

Arras, P., & Lai, D. 1999a, ApJ, 519, 745.

Bazan, G., & Arnett, D. 1998, ApJ, 496, 316.

Bethe, H. A. 1997, ApJ, 490, 765.

Blaskiewicz, M., Cordes, J. M., & Wasserman, I. 1991, ApJ, 370, 643.

Burrows, A., & Hayes, J. 1996, Phys. Rev. Lett., 76, 352.

Burrows, A., Hayes, J., & Fryxell, B. A. 1995, ApJ, 450, 830.

Burrows, A., & Lattimer, J. M. 1986, ApJ, 307, 178.

Caraveo, P. A., & Mignani, R. P. 1999, A&A, 344, 367.

Cordes, J. M., & Chernoff, D. F. 1998, ApJ, 505, 315.

Cordes, J. M., Romani, R. W., & Lundgren, S. C. 1993, Nature, 362, 133.

Cordes, J. M., Wasserman, I., & Blaskiewicz, M. 1990, ApJ, 349, 546.

Deshpande, A. A., Ramachandran, R., & Radhakrishnan, V. 1999, A&A, 351, 195.

Dewey, R. J., & Cordes, J. M. 1987, ApJ, 321, 780.

Fryer, C., Burrows, A., & Benz, W. 1998, ApJ, 496, 333.

Fryer, C. L., & Heger, A. 2000, ApJ, 541, 1033.

Fryer, C. L., & Kalogera, V. 1997, ApJ, 489, 244.

Goldreich, P., Lai, D., & Sari, R. 1998, MNRAS, 309, 542.

Hansen, B. M. S., & Phinney, E. 1997, MNRAS, 291, 569.

Harrison, E. R., & Tademaru, E. 1975, ApJ, 201, 447.

Heger, A., Langer, N., & Woosley, S. E. 2000, ApJ, 528, 368.

Helfand, D. J., Gottlieb, E. V., & Halpern, J. P. 2001, ApJ, submitted.

Hernquist, L., Benz, W., Hix, J., Fryer, C. L., & Colgate, S. A. 1994, ApJ, 435, 339.

Hester, J. J., et al. 1995, ApJ, 448, 240.

Ho, W. C. G., & Lai, D. 2000, ApJ, 543, 386.

Iben, I., & Tutukov, A. V. 1996, ApJ, 456, 738.
Rankin, J. M. 1990, ApJ, 352, 247
Romani, R. W., & Yadigaroglu, I.-A. 1995, ApJ, 438, 314
Spruit, H., & Phinney, E. S. 1998, Nature, 393, 139
Tauris, T. M., et al. 1999, MNRAS, 310, 1165
Thompson, C., & Duncan, R. C. 1993, ApJ, 408, 194
———. 1996, ApJ, 473, 322
van den Heuvel, E. P. J., & van Paradijs, J. 1997, ApJ, 483, 399
Vasisht, G., & Gotthelf, E. V. 1997, ApJ, 486, L129
Vilenkin, A. 1995, ApJ, 451, 700

Wang, L., Howell, D. A., Höflich, P., & Wheeler, J. C. 2001, ApJ, in press (astro-ph/9912033)
Weaver, T. A., & Woosley, S. E. 1993, Phys. Rep., 227, 65
Weisberg, J. M., Romani, R. W., & Taylor, J. H. 1989, ApJ, 347, 1030
Weisskopf, M. C., et al. 1999, AAS Meeting, 195, 112.04
Wex, N., Kalogera, V., & Kramer, M. 2000, ApJ, 528, 401
Wu, Y., Matzner, C. D., & Arras, P. 2001, ApJ, 549, 1011
Wycko†, S., & Murray, C. A. 1977, MNRAS, 180, 717