The Astrophysical Journal, 456:738–749, 1996 January 10

ON THE ORIGIN OF THE HIGH SPACE VELOCITIES OF RADIO PULSARS[1]

Icko Iben, Jr.,[2] and Alexander V. Tutukov[2,3]
Received 1995 April 13; accepted 1995 July 14

ABSTRACT

Most observed radio pulsars have high peculiar space velocities covering the range 20–1000 km s^{-1}, although their unevolved OB star progenitors have peculiar space velocities which are among the lowest in the Galaxy. An evolutionary scenario model of the Galactic population of neutron stars shows that the evolution of massive close binaries which takes into account the recoil velocity achieved in response to mass loss in supernova explosions, but ignores a possible additional "natal kick," can produce single neutron stars with space velocities in the range of 10–1000 km s^{-1}, the highest velocities being achieved in the second supernova explosion which unbinds (most) massive binaries. The theoretical distribution of space velocities is consistent, within the uncertainties, with the transverse velocity distribution for radio pulsars in the 500 pc neighborhood of the Sun. The same model explains observed space velocities of OB runaway stars, massive X-ray binaries, and close binary neutron stars.

Progenitors of neutron stars which become radio pulsars are hydrogen-free and so experience supernova explosions which are presumably of Types Ib and Ic. The predicted birthrate of such supernovae, and therefore also of radio pulsars, is $\sim$0.007 yr^{-1}, compared with a predicted Type II supernova birthrate of $\sim$0.021 yr^{-1}. Within the uncertainties, these estimates are consistent, respectively, with existing semiempirical estimates of the pulsar formation rate and estimates of the frequency of supernova explosions. The fact that the predicted birthrate of radio pulsars is 4 times smaller than the predicted combined birthrate of supernovae of Types Ib, Ic, and II, coupled with the fact that pulsar radiation is beamed, suggests that fewer than $\sim$10% of all radio pulsars are associated with diffuse supernova remnants, regardless of age.

In the scenario model with no ad hoc natal kicks, the absence of observed radio pulsars in wide binaries is interpreted as the result of the slow rotation of young neutron stars formed in Type II supernova explosions of single stars or of components of wide, detached binaries. The absence of a close companion which can supply matter and angular momentum to either the presupernova or to the neutron star leaves the neutron star with insufficient angular momentum to be a radio pulsar.

A final conclusion about the role of single stars and components of wide binaries in the formation of radio pulsars requires that the pulsar space velocity distribution be known for velocities less than $\sim$20 km s^{-1}. The scenario model predicts as many neutron stars with velocities less than 20 km s^{-1} as there are in the 20–1000 km s^{-1} range (whether or not these neutron stars are pulsars). If further observations show the birthrate of low-velocity neutron stars to be comparable to the birthrate of high-velocity ones, this would be a direct demonstration that nature does not require an ad hoc asymmetric kick. If spin periods of the low-velocity group are typical of the spin periods already known ($\lesssim$3 s), rather than of the order of 100–300 s, as is expected if the angular velocity of presupernova cores is comparable to the angular velocity at the presupernova surface, one could infer that the core of the precursor of a Type II supernova spins much faster than do surface layers, and that, therefore, accretion on a neutron star is not the primary reason for observed radio pulsar spin periods. On the other hand, if further observations reveal a real (rather than a selection-induced) paucity of low-velocity pulsars, this would provide strong support for the current prediction that massive single stars and components of wide binaries do not produce radio pulsars and that most radio pulsars have their origin in close binaries.

Subject headings: binaries: close — pulsars: general — stars: evolution — stars: kinematics — stars: neutron — supernovae: general

1. INTRODUCTION

Several years after their discovery, radio pulsars were recognized as rapidly moving objects with typical peculiar space velocities of the order of $\sim$100 km s^{-1} (Gunn & Ostriker 1970). The variation of rotation period with height above the Galactic plane displayed by the first 41 known radio pulsars suggested that young radio pulsars are more strongly concentrated to the Galactic plane than are old ones. This fact, together with the known high rate of transverse motion of the Crab pulsar, led to the inference that radio pulsars acquire a space velocity $\sim$100 km s^{-1} at birth. The massive OB star progenitors of pulsars, and the interstellar gas from which they were recently formed, have a dispersion in space velocities of only $\sim$10–20 km s^{-1} (e.g., Wielen 1992).

The high space velocities of radio pulsars were not at first thought to be very surprising, given that, long before the discovery of pulsars, a class of OB stars with space velocities of 50–200 km s^{-1} had been identified. Members of this class are

[1] Supported in part by the NSF grants AST91-13662 and AST94-17156, the Russian Fund for Fundamental Research grant 93-02-2893, the ESO C&EE Programme grant A01-019, and the International Science Foundation grant MPT000.

[2] Astronomy Department, University of Illinois, 1002 W. Green Street, Urbana, IL 61801; icko@sirius.astro.uiuc.edu.

[3] Institute of Astronomy of the Russian Academy of Sciences, 48 Pyatnitskaya Street, Moscow 109017, Russia; atutukov@inasan.rssi.ru.

called "runaway" stars and the origin of their velocities was explained by Zwicky (1957) and Blaauw (1961) as the consequence of supernova explosions in close binaries. To acquire a high space velocity, the binary need not be disrupted; for a spherically symmetric supernova explosion in a binary of low eccentricity, all that is required is that the mass remaining in stellar remnants is larger than the mass lost in the supernova explosion (Boersma 1961). In this case, a relatively low mass relativistic product of the supernova explosion will accompany the runaway OB star, forming a short-period binary. Gunn & Ostriker (1970) applied the binary scenario to explain the high space velocities of radio pulsars, explicitly invoking configurations in which the supernova explosion leads to disruption. Orbital velocities of the closest massive binary stars (those in which stellar sizes are comparable with the orbital separation) are several hundreds of km s^{-1}. In the process of disintegration of such systems, both products of the disintegration acquire space velocities which are significantly larger than those of typical massive stars. Thus, the initial explanation of the high space velocities of radio pulsars was attributed to the formation of a significant fraction of pulsar progenitors in close binaries with high orbital velocities.

In recent years, it has become clear that some massive stars can acquire high space velocities through the disintegration of young compact multiple systems with $\geq$three stars in which a supernova explosion has not occurred. The formation of such systems has been studied numerically by Bonnell & Bate (1994). In systems in which the initial distances between all components are comparable, a dynamical instability manifests itself by an ejection (or "evaporation"), with remaining members being left in more stable configurations than before (Harrington 1975). For example, unstable triple systems typically resolve the instability by ejecting the lightest component with a speed which is close to the orbital velocities of the two remaining bound members. Triple systems are stable if the ratio of orbital periods (the rotational period $P_{\rm outer}$ of a distant companion divided by the rotational period $P_{\rm inner}$ of the inner binary) is in the range $\sim$2.4–6.3 when the ratio of the mass of the distant component relative to the mass of the inner binary is in the range 0.01–100 (Kiseleva, Eggleton, & Anosova 1994). In 35 triple systems with well-known orbital parameters, these criteria appear to be satisfied (Fekel 1981).

It is of interest to know how frequently this evaporation process produces runaway stars relative to how frequently close binary stars produce them. The distribution N of binaries over the semimajor axis A, as found by Popova, Tutukov, & Yungelson (1982), can be approximated by (Iben & Tutukov 1984)

$$dN = 0.2\, d \log A \,. \tag{1}$$

If one assumes that this distribution is also valid for the larger semimajor axis of triple systems, an upper limit on the possible relative number of runaway stars arising in this way can be estimated. This assumption seems reasonable, since, in essence, equation (1) reflects the distribution of protostellar clouds over their partial angular momentum. For a triple system in which components are of comparable mass, the critical ratio of orbital periods is ~ 4 (Kiseleva et al. 1994), and the ratio of semimajor axes will be, according to Kepler's third law, about 2.5, giving $d \log A \sim 0.4$. Thus one may estimate that about 8% of all triple stars are born in unstable configurations.

To determine what fraction of unstable triple star configurations can produce single runaway stars with space velocities larger than ~ 30 km s^{-1}, we adopt a lower limit on orbital separation of $\sim 10\ R_\odot$ (to prevent merger), and an upper limit of $\sim 100\ R_\odot$ (to ensure large enough orbital velocities). Once again using equation (1), one may estimate that only $\sim 20\%$ of all dynamically unstable systems contain massive stars with appropriately large orbital velocities. Altogether, then, no more than $\sim 2\%$ of young massive stars in triple systems achieve high space velocities, and this constitutes only a small fraction of all known massive runaway OB stars. The disintegration of triple systems containing moderate mass (2–10 $M_\odot$) stars also produces a few high space velocity stars, and this mechanism for producing high space velocity stars may also operate in systems of multiplicity higher than 3.

In some sense, the disintegration of multiple systems as a possible mode of formation of runaway stars coincides with the Zwicky-Blaauw supernova recoil mechanism, in that both mechanisms rely on linear momentum conservation and on high orbital velocities. The recoil mechanism driven by supernova explosions has been applied widely for estimates of possible space velocities of radio pulsars (Gott, Gunn, & Ostriker 1970; van den Heuvel & Heise 1972, Tutukov & Yungelson 1973; Kornilov & Lipunov 1984; Dewey & Cordes 1987; Bailes 1989; Narayan & Ostriker 1990; and others).

Almost simultaneously with the recoil explanation of high space velocity pulsars, Shklovski (1970) appealed to an ad hoc, asymmetric, "natal kick" imparted to the neutron star at birth to explain, among other things, the existence of nonspherically symmetric extended supernova remnants. In the intervening time, it has been recognized that asymmetries are also introduced by interaction between the matter ejected in the supernova explosion and an inhomogeneous interstellar medium.

Several physical processes have been proposed to support the kick idea. Harrison & Tademaru (1975) and Helfand & Tademaru (1977) proposed a "rocket" effect to accelerate a young magnetic neutron star. Morris, Radhakrishnan, & Shukre (1976) showed that, if this mechanism were operating, there should be a correlation between the pulsar spin axis and the space velocity vector. Such a correlation was not found for the first 26 pulsars with known transverse motions (Lyne, Anderson, & Salter 1982). Chugai (1984) suggested that, if the dipole magnetic field strength is about 5×10^{14} G, neutrino chirality (polarization of electron and positron spins in a strong magnetic field) might supply a forming neutron star with a kick velocity of about 200 km s^{-1}. Such a large magnetic field strength significantly exceeds observed field strengths. For typical field strengths of a few times 10^{12} G, the kick is estimated to be smaller than ~ 3 km s^{-1} (Chugai 1984), which is clearly not sufficient to explain observed radio pulsar space velocities.

Recent two-dimensional hydrodynamical models of supernova explosions which form neutron stars suggest a mechanism whereby a neutron star may acquire a space velocity as large as ~ 200 km s^{-1} due to large-scale convective motions in the rotating core of the supernova (Herant, Benz, & Colgate 1992; Janka & Müller 1994, & references therein). Citing the results of a linear stability analysis by Chandrasekhar (1961), Herant et al. (1992) suggest that, in the neutrino-driven convective region of a forming neutron star, the most unstable mode might be the $l = 1$ mode, and that "accretion on one side of the proto-neutron star" might account for kick velocities of the order 100 km s^{-1}, as inferred by Dewey & Cordes (1987) from a comparison between theoretical models of the neutron star space velocity distribution and the observed distribution. Constructing three-dimensional models, Khokhlov (1994) suggests that the tendency of large-scale motion to dominate in the flow is possibly an artifact of the two-dimensional approach, but Burrows, Hayes, & Fryxell (1995), who calculate the progress of about 30 convective overturns in a two-dimensional calculation, find a large range of scale lengths which do not cascade to the $l = 1$ mode. Thus, the possibility of achieving a large kick with this particular mechanism does not appear to work, although, adding a strong magnetic field which tranforms three-dimensional turbulence into an effective two-dimensional turbulence might possibly amplify the large-scale motion and save the mechanism.

Welcome searches for possible physical mechanisms for a large asymmetric kick continue. For example, Burrows et al. (1995) suggest that fluctuations in the accretion flux may produce kicks of order 180 km s^{-1} and that recoil velocities due to anisotropic netrino emission in the collapsing core could contribute up to 300 km s^{-1}. Burrows & Hayes (1995) find that imposed inhomogeneities in the density are preserved during collapse and argue that kicks up to 400–500 km s^{-1} might be achieved in this way. However, these mechanisms are, as yet, just suggestions, and much more work is required to determine which of the possibilities, if any, can actually occur without the imposition of ad hoc initial conditions. In the meantime, it is important to establish whether or not the observations provide incontrovertible evidence for large asymmetric kicks.

2. RADIO PULSAR SPACE VELOCITIES

There are three principal ways to estimate the space velocity of a radio pulsar. The first and most direct method uses an observed proper motion and a distance to estimate the transverse component of the space velocity. The distance is usually estimated from an observed dispersion measure by assuming an average electron density. For an isotropic distribution in velocity space, the actual space velocity v_{sp} is, on average $4/\pi$ times the transverse space velocity v_t.

A second method focuses on the distribution of pulsars in the z direction (perpendicular to the Galactic plane). The usual assumption is that most radio pulsars are born in the Galactic plane and that the characteristic timescale ($\tau_c = P/2\dot{P}$, where P is the pulsar spin and $\dot{P}$ is its time derivative) coincides with age. The distance z is estimated from observed Galactic latitude in conjunction with a line-of-sight distance which is, once more, estimated from the dispersion measure and an assumed electron-density distribution along the line of sight. For an isotropic stellar distribution in velocity space, the actual space velocity is, on average, $v_{sp} = 2v_z \sim 2z/\tau_c$. The shortcomings of this method include the uncertainty in distance estimates and the fact that τ_c is only an approximate indication of age.

The third method uses scintillation observations to estimate space velocities (Lyne & Smith 1982; Cordes 1986). The scintillation velocity is dominated by the transverse velocity. The resulting distribution in transverse velocities is very broad, ranging up to 150 km s^{-1}, with a poorly populated tail extending to $\sim$300 km s^{-1}. The median value of the scintillation tranverse velocity is only $\sim$60 km s^{-1}. The relatively low value of this median velocity is probably due to the fact that the scattering gas is concentrated to the Galactic plane, reducing estimates of v_t for high z pulsars (Harrison, Lyne, & Anderson 1993). There is a very large dispersion in the relationship between individual velocities inferred from the z distribution and those inferred via the scintillation method

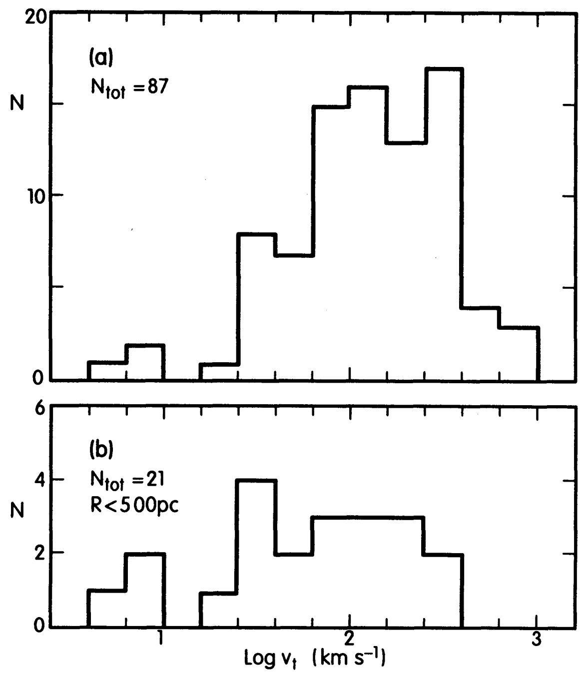

FIG. 1.—The observed distribution of radio pulsars with known proper motions over their transverse velocities (from Harrison et al. 1993). Fig. 1*a* includes all pulsars from Tables 3 and 4 in Harrison et al. and Fig. 1*b* contains only pulsars closer than $\sim$500 pc.

(Cordes 1986). Nevertheless, scintillation data support the view that most radio pulsars have high space velocities.

Proper motions remain the most reliable source of data for estimating pulsar space velocities. The currently most complete list of proper motions (87 pulsars) is given by Harrison et al. (1993). They use a specific model of the electron density distribution in the Galaxy (Lyne, Manchester, & Taylor 1985) in conjunction with observed dispersion measures to obtain the distribution of pulsars with respect to transverse velocity shown in Figure 1*a*. The distribution is broad and the maximum and minimum velocities differ by a factor of $\sim$140. The median velocity is $\sim$130 km s^{-1}.

The Lyne et al. (1985) electon-density model is axisymmetric. It has two components plus the Gum nebula. Selecting 38 pulsars for which independent distance estimates have been made (Manchester & Taylor 1981), model parameters are chosen in such a way as to minimize the differences between dispersion-measure distances and the independently estimated distances. Most of the independent distance estimates use Doppler shifts of 21 cm absorption features in conjunction with a model Galactic rotation curve. From Figure 3 in Lyne et al. (1985), only upper or lower limits exist for 12 of the calibration sources, and the error bar on distance estimates for 12 sources is from 0.25 dex to greater than 0.3 dex. With the adopted model, dispersion-measure distances to approximately 12 sources differ from the independently estimated distances by over a factor of 2.

Given these uncertainties, Taylor & Cordes (1993) have constructed a more complicated nonaxisymmetric model of the electron-density distribution in the Galaxy which, among other things, takes into account electron-density enhancements in spiral arms. The model parameters are chosen to give the best distance fits to 74 pulsars for which independent distance estimates have been made (Frail & Weisberg 1990). Lyne &

Lorimer (1994) use the new model to study the distribution with respect to v_t of the radio pulsars in the Harrison et al. (1993) list and include in their study about two dozen other pulsars for which scintillation or proper motion distance estimates can be made. For the pulsars for which dispersion measures are used, the average electron densities along a line of sight are typically a factor of 2 smaller than when the Lyne et al. (1985) electron-density model is used. The resulting distribution in number versus v_t extends from ~ 10 km s^{-1} to ~ 2000 km s^{-1} and the median transverse velocity is ~ 220 km s^{-1}. Lyne & Lorimer infer an average space velocity of 450 km s^{-1}, compared with a value of 190 km s^{-1} derived earlier by Harrison et al. (1993).

The implications of such a large space velocity, if interpreted as a mean asymmetric kick velocity, are sufficiently dramatic that one might wonder whether the most recent electron-density model gives overall results which are more reliable than its predecessors. We are not in a position to answer this question, but are able to ask if, in constructing a number-velocity distribution, there may be observational selection effects which have not yet been properly taken into account and which act in a direction as to reduce the median velocity of the distribution.

Apart from the uncertainty in the distance scale due to the requirement that the electron density be known along the entire path from the pulsar to the Earth, an evident disadvantage of the proper motion approach to space velocities is an insensitivity to low velocities at large distances. This is illustrated by Figure 1*b*, which makes use of the information in Figure 2 where the 87 pulsars in Harrison et al. (1993) are shown in the v_t-distance (D) plane (using the Lyne et al. 1985 electron-density model). The straight line labeled $v_{\min}$ is a lower boundary for measurable transverse velocities. It is evident that only for pulsars within a distance $D \gtrsim 500$ pc from the Sun can transverse velocities be extracted from the noise if they are less than 10 km s^{-1}. For $D > 500$ pc, space velocities can be determined only for radio pulsars moving more rapidly than this, and the minimum measurable transverse velocity increases linearly with the distance. In Figure 1*b*, only those pulsars that are within 500 pc of the Sun (assuming the Lyne et al. 1985 electron-density model) are included. It is evident that the distribution has become rather uniform and well populated

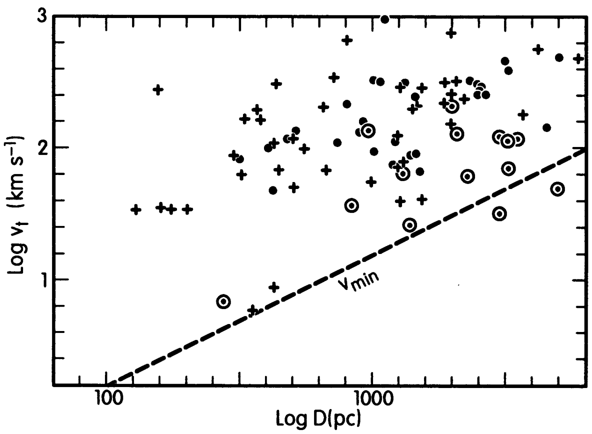

FIG. 2.—Observed transverse velocities of radio pulsars versus their distances D from the Sun (from Harrison et al. 1993). Plus signs identify the 44 pulsars from Table 3 and filled circles identify the 43 pulsars from Table 4. Pulsars with uncertain proper motion ($\sigma_v \geq v$) are identified by circled dots.

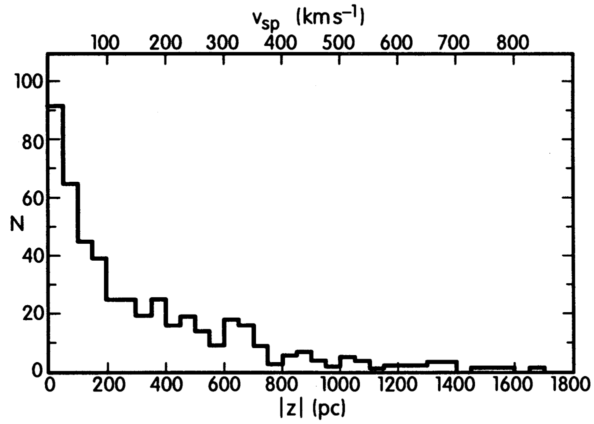

FIG. 3.—The distribution of Galactic disk pulsars over their absolute distances $|z|$ from the Galactic plane (from Taylor et al. 1993). The upper scale shows the space velocity which a pulsar must have to reach the corresponding distance from the plane in a time equal to $\tau_c \sim 4 \times 10^6$ yr, the average pulsar characteristic timescale (Taylor et al. 1993). It is assumed that $v_z = 0.5 v_{sp}$.

over the velocity range 10–400 km s^{-1}, and the median transverse velocity has decreased from ~ 130 km s^{-1} to ~ 70 km s^{-1}.

In Figure 3 is shown the z distribution of Galactic disk radio pulsars (i.e., those which are not in globular clusters) as given by Taylor, Manchester, & Lyne (1993). This distribution can be interpreted as consisting of two components, one of scale height ~ 100 pc, the other a very broad distribution extending to ~ 2 kpc. The median value of z for the entire sample is ~ 200 pc. In the Taylor et al. (1993) data, there is also evidence for a correlation between z and τ_c showing that old pulsars have significantly larger scale heights than do younger ones. The correlation suggests an average z-component space velocity of $v_z \sim 170$ km s^{-1} (Taylor et al. 1993). This estimate depends directly on the distance scale, and it is worth pointing out that the long tail in the z distribution is evidence for a significant dispersion in pulsar space velocities. For example, to achieve $z = 1.6$ kpc in 4×10^6 yr (the median τ_c for Galactic pulsars according to Taylor et al. 1993), the speed in the z direction must be ~ 400 km s^{-1}. But half of all known pulsars have $z \leq 200$ pc. Keeping in mind that the initial average z (prior to the formation of the second neutron star in a binary system; see § 4) is ~ 100 pc, it follows that, for the pulsars with $z \leq 200$ pc, the z velocity satisfies $v_z \leq 50$ km s^{-1}, so that $v_{sp} \leq 100$ km s^{-1}. This is consistent with the statistics for nearby pulsars (Fig. 1*b*) which show that there are about as many pulsars with $v_t \leq 60$ km s^{-1} as there are with $v_t > 60$ km s^{-1}. The z distribution (Fig. 3) demonstrates the existence of a relatively small number of high space velocity pulsars with v_{sp} up to ~ 800 km s^{-1}.

3. ON THE INTRINSIC DISTRIBUTION OF RADIO PULSARS WITH RESPECT TO SPACE VELOCITY

The observed distribution of nearby ($D \leq 500$ pc) pulsars with respect to transverse velocity (Fig. 1*b*) may be used to estimate the intrinsic (at birth) distribution of radio pulsars with respect to space velocity. The average transverse velocity of the nearby sample is only ~ 68 km s^{-1} (instead of ~ 130 km s^{-1} for all of them; Fig. 1*a*), showing that observational selection can significantly influence distributions. The observed distribution function $N(v_t)$ for all pulsars with known proper

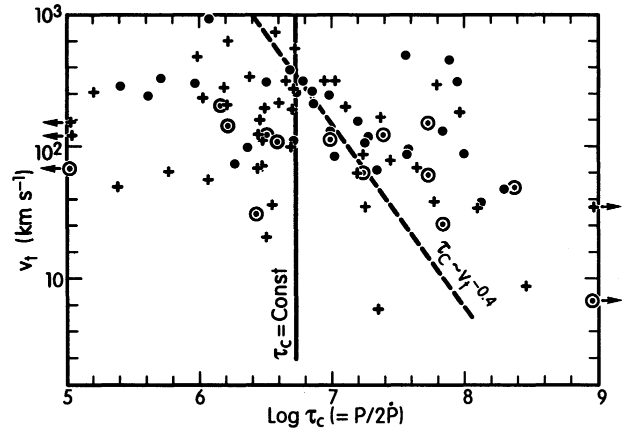

FIG. 4.—Transverse velocities of pulsars (Harrison et al. 1993) vs. their characteristic lifetimes τ_c (Taylor et al. 1993). Symbols have the same meaning as in Fig. 2. The dashed and the solid lines show two adopted test correlations $\tau_c(v_t)$.

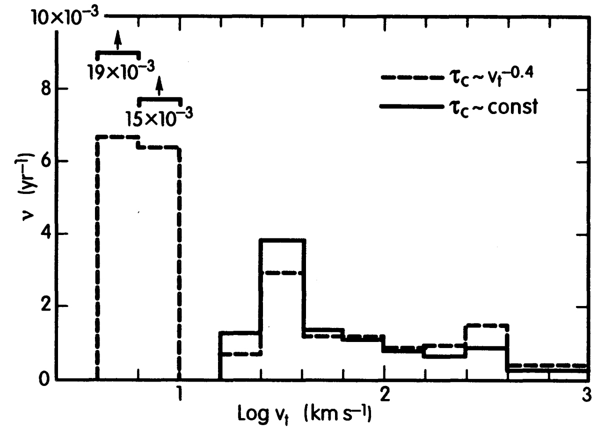

FIG. 6.—Birth functions $\nu(v_t) = N(v_t)/(S\tau_c)$ of nearby pulsars with known proper motions as derived from pulsar numbers $N(v_t)$ (Fig. 1*b*) and selection functions $S\tau_c$ (Fig. 5). The birth functions are normalized to give a total birth-rate of $\sim$0.007 yr^{-1} for radio pulsars with $v_t \geq 10$ km s^{-1}.

motions is related to the birth function $\nu(v_t)$ by

$$N(v_t) = \nu(v_t) S\tau_c(v_t) , \tag{2}$$

where S is an appropriate Galactic surface area and it is supposed that τ_c could be a function of v_t. We assume (see Fig. 2) that (1) pulsars homogeneously fill disks with surface areas S which are proportional to D^2; (2) $D \propto v_t$ for $D \leq 6.3$ kpc; and (3) S = constant for $D \geq 6.3$ kpc. In Figure 4, transverse velocities from Harrison et al. (1993) are plotted against characteristic lifetimes (see also Fig. 1 in Lyne & Lorimer 1994). We make two choices for the function $\tau_c(v_t)$. The dashed line (along which $\tau_c \sim v_t^{-0.4}$) has the property that, in each of 11 evenly spaced, adjacent intervals of log v_t, there are roughly as many points to the right of the line as there are to the left of the line. The vertical solid line in Figure 4 is positioned in such a way that there are as many points to the right of it as there are to the left of it. The resulting functions $S\tau_c$ are shown in Figure 5. The curves have been normalized so that $S\tau_c = 1$ when $v_t = 100$ km s^{-1} ($D \sim 6$ kpc; Fig. 2). For the choice $\tau_c \sim v_t^{-0.4}$ (*dashed line*), $S\tau_c$ decreases with decreasing distance and decreasing minimum velocity due to the decrease in available surface area; for large distances and large minimum velocity it decreases with increasing distance due to the decrease in average pulsar age. For the choice τ_c = constant, $S\tau_c$ is constant for $v_t \geq 100$ km s^{-1}.

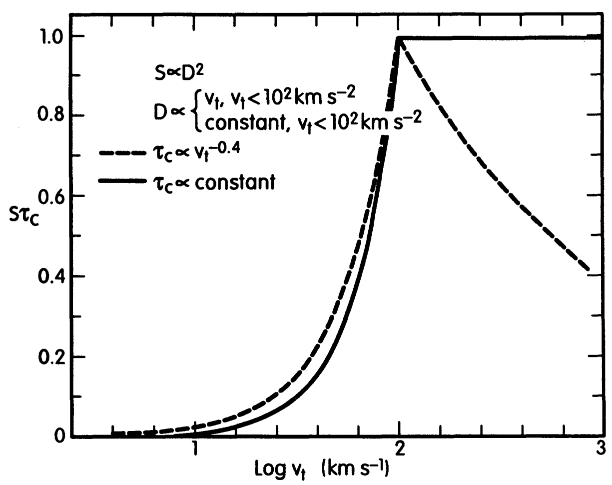

FIG. 5.—The selection function $S\tau_c$ (product of the surface area S of the accessible part of the Galactic disk and the lifetime τ_c) as a function of the transverse velocity v_t of pulsars with known proper motions. The solid line holds if pulsar lifetimes do not depend on v_t and the dashed line holds if $\tau_c \propto v_t^{-0.4}$.

The resulting birth functions are shown in Figure 6. To enable comparison with theoretical scenario model results, both birth functions have been normalized so that $\int \nu(v_t) d \log v_t \sim 0.007$ yr^{-1}, the theoretical birthrate of neutron stars in massive close binary stars (see § 6). The birth functions maintain the wide dispersion in v_t from $\sim$10 to $\sim$1000 km s^{-1} found in the observed distribution (Fig. 1*b*), but, for both choices of τ_c, the three slowest pulsars close to the Sun have been transformed into a well-populated family comprising about half of all pulsars. The three pulsars on which this surprising transformation hinges are really moving very slowly—their low velocities cannot be explained as a result of the projection of a high space velocity, as the probability of such a projection is very small for as many as three out of 87 pulsars in a spherically symmetric distribution of space velocities with v_{sp} typically $\geq$100 km s^{-1}. The role of these stars in determining the birth function may well be overestimated because of the unavoidable decrease in the selection function $S\tau_c$ (Fig. 5) at low space velocities. Although errors related to overestimating distances to close objects do not appreciably affect the result, errors relating to underestimating distances to close objects significantly increase the estimated local density of objects.

Helfand & Tademaru (1977), Tutukov, Chugai, & Yungelson (1984), and Narayan & Ostriker (1990) have inferred that about half of all radio pulsars have relatively low ($\leq$50 km s^{-1}) space velocities at birth. This inference also follows from the distribution function defined by the observational sample of nearby pulsars (Fig. 1*b*), and from the birth function derived therefrom (Fig. 6). These concordant inferences would seem to exclude the possibility of a high ($\geq$100 km s^{-1}), universal, ad hoc kick for all radio pulsars.

4. THE SPACE VELOCITIES OF MASSIVE STARS

According to the standard scenario of massive close binary star evolution (van den Heuvel & Heise 1972; Tutukov & Yungelson 1973), there are two observable consequences of the first supernova explosion in a massive binary: runaway stars and massive X-ray binaries. The space motions of these two products are of relevance in the current context.

The observed distribution of OB stars over their space velocities as given by Stone (1979) is shown in Figure 7*a* for stars at any distance and in Figure 7*b* only for stars within 1 kpc of the Sun. Note that distance estimates do not depend on a model for the electron-density distribution in the Galaxy! Runaway stars are well represented in both figures. A consensus estimate of what fraction of all OB stars belongs to the runaway family has not yet emerged. Stone (1979) considers the numbers of slow ($v_{sp} \leq 25$ km s^{-1}) and fast ($v_{sp} \geq 25$ km s^{-1}) OB stars to be approximately equal. Conti, Leep, & Lorre (1977) recognize as runaway stars (defined as those with $v_{sp} \geq 40$ km s^{-1}) only about 7% of all O stars. Isserstedt & Feitzinger (1981) find that ~ 12% of all O stars have $v_{sp} \geq 50$ km s^{-1}. In a table of other estimates compiled by Gies & Bolton (1986), this fraction varies for existing samples from a few percent to about 50%.

All estimates show that the fraction of runaway stars among massive stars increases with stellar mass, and this pattern follows naturally from the theory of close binary star evolution. More massive components form a more massive helium core, and, therefore, the mass lost in the subsequent supernova explosion is also larger. Conservation of linear momentum ensures that, in general, the remaining gravitationally bound binary has a higher space velocity. A corollary is that most binary runaway stars have a close relativistic component—a neutron star or black hole—a prediction verified early on in the case of HD 59543, which is a B5 star in a highly eccentric orbit ($e = 0.52$) with an unseen companion of mass estimated by Gott (1972) to be $\geq 1.6\ M_{\odot}$.

To check other systems for the presence of unseen companions, Stone (1982) has monitored 10 very probable O-type runaway stars. Four are positively identified as velocity variables and three as possible variables. Such a large percentage of close binaries among runaway stars is striking, especially when the expected low mass ratio of components is taken into account. The high duplicity of high space velocity OB stars is also an indication that most runaway stars are rather close binaries which have typically experienced a common envelope stage. The remaining "single" runaway stars in the Stone (1982) sample with unseen variations in radial velocity either have inappropriate orbital inclinations, or are really single stars which have lost their companions after the supernova explosion or after the disruption of a compact unstable multiple system. In any case, the empirical results show that most runaway stars have relativistic companions. This is a strong argument against a large, randomly oriented natal kick exceeding ~ 150 km s^{-1}, which would destroy these binaries at the moment of neutron star formation. Thus, the high space velocities of runaway stars can be adequately explained by a recoil due to mass loss in a spherically symmetric supernova explosion which occurs after a significant contraction (during a common envelope event) of the semimajor axis in an initially close binary with a fairly large initial mass ratio.

After the first supernova event in a close binary, the secondary component eventually expands until it almost fills its Roche lobe. Accretion from the wind emitted by the secondary forms a bright, easily observable X-ray source. According to the scenario for massive close binary evolution, high-mass X-ray binaries (HMXBs) have high space velocities and an extended distribution in the *z*-direction (e.g., Iben, Tutukov, & Yungelson 1995a). The distribution of observed HMXBs over their space velocities, as estimated from their radial velocities (van Oijen 1989), is shown in Figure 8. This distribution is similar to the distribution of runaway stars (Fig. 7) and is easily explained by the scenario model (see Fig. 6 in Iben et al. 1995a). The possible slight shift of the HMXB distribution (Fig. 8) to mean velocities larger than in the runaway star distribution

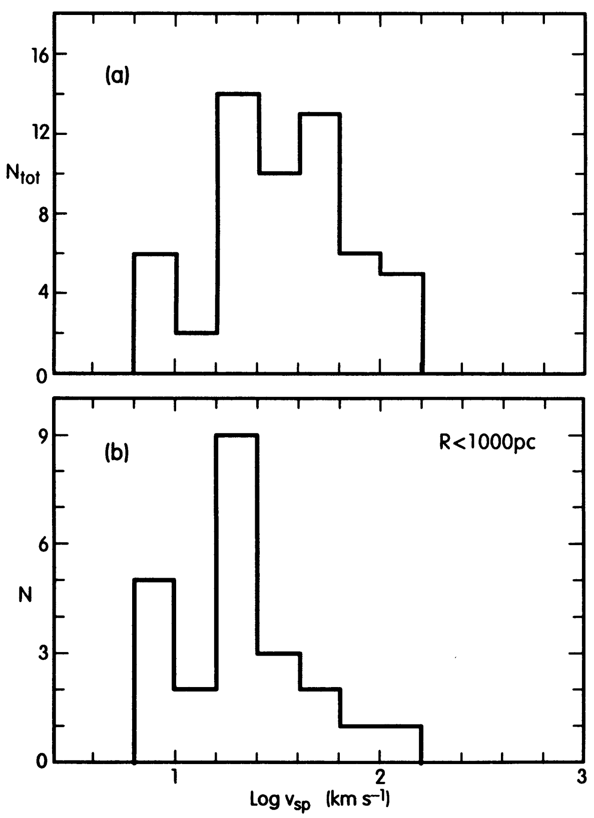

FIG. 7.—The distribution of O stars over their space velocities (Stone 1979). Fig. 7*a* includes all stars and Fig. 7*b* contains only stars within a disk of radius 1 kpc around the sun.

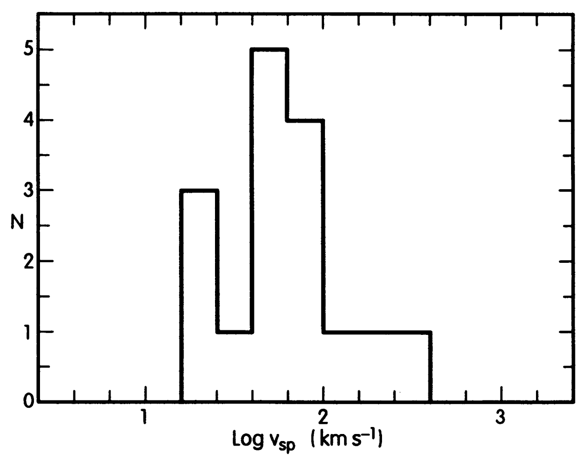

FIG. 8.—The distribution of space velocities of massive X-ray binaries according to van Oijen (1989). The observed radial peculiar velocities in van Oijen's Table 6 have been increased by a factor of 2 to take into account the two components of velocity perpendicular to the line of sight.

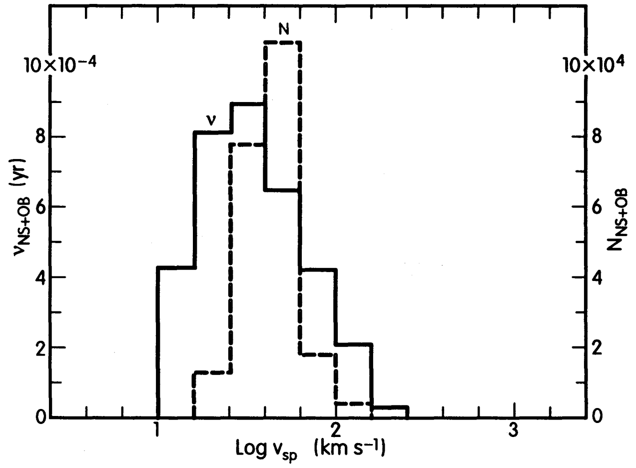

FIG. 9.—The model distribution of OB stars with unseen relativistic components over their space velocities (from Tutukov & Yungelson 1993). The histogram labeled v shows the birthrate of runaway stars as a function of space velocity and the histogram labeled N shows the distribution of current numbers of these stars in the Galaxy.

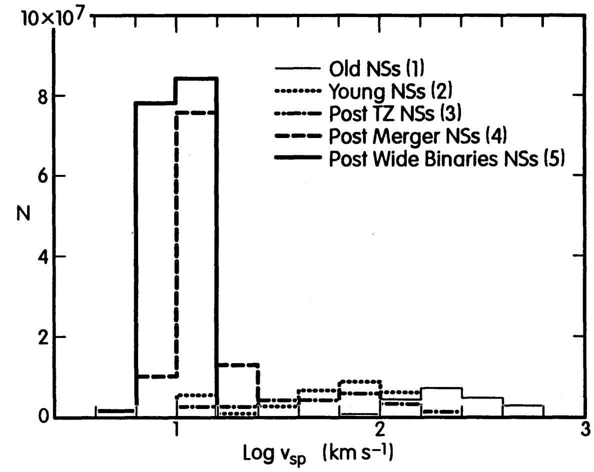

FIG. 10.—The model distribution of single Galactic neutron stars over their space velocities on the assumption that all of them have the same lifetime, 1.5×10^{10} yr. There are five different classes: (1) "old" neutron stars which are products of the first supernova event in a massive close binary and are "freed" during the second supernova explosion; (2) "young" neutron stars which are products of the second supernova event or of the first supernova event in binaries which become unbound during this first event; (3) post–Thorne-Żytkow objects—neutron stars which have shed an extended envelope gained in a merger; (4) neutron stars produced by single stars formed after merging of components of close binary stars; (5) neutron stars formed in wide binaries which become unbound, usually after the second supernova event.

can be explained naturally by the fact that, on average, progenitors of HMXBs have smaller semimajor axes than do progenitors of typical runaway stars. This is a result of observational selection, since the duration of the X-ray stage is longer in closer systems (e.g., Iben et al. 1995a) and closer systems attain larger recoil velocities after supernova explosions. The effect is also evident on comparing Figures 7 and 8 with Figure 9, where theoretical distributions of birthrate and number versus space velocity are shown for all O stars in a binary with a neutron star companion, whether or not they are HMXBs (Tutukov & Yungelson 1993). In summary, the high space velocities of HMXBs and massive runaway O stars with optically unseen companions can be explained as a result of the recoil due to mass loss in a spherically symmetric supernova explosion, and there is no need to invoke an extra, ad hoc kick.

5. A THEORETICAL DISTRIBUTION OF NEUTRON STARS WITH RESPECT TO SPACE VELOCITY

The distribution of neutron stars over their space velocities as modeled by Tutukov & Yungelson (1993) is shown in Figure 10. The initial dispersion of space velocities of massive stars has been assumed to be ~ 10 km s^{-1} (Wielen 1992). The model neutron-star birthrate is ~ 0.028 yr^{-1}, with neutron stars forming almost equally frequently in close (with mass exchange between components) and wide (without mass exchange) massive binaries. A variation within the uncertainties in the initial distribution of binaries over semimajor axis and in the mass ratio of components leads to a factor of 2 variation in the estimated birthrate of neutron stars. About 80% of all neutron stars are estimated to be single stars. The main channels for the production of single neutron stars are the second supernova explosion ($\sim 55\%$), merging of close binary components ($\sim 36\%$), and the disruption of the binary in the first supernova explosion ($\sim 9\%$). The first supernova explosion transforms surviving binaries into runaway stars, and the second explosion usually disrupts the binary, adding to the space velocity.

There are five different components in the theoretical distribution of neutron stars (see Fig. 10). Neutron stars which are produced by the first explosion and become free after the second supernova explosion constitute the family with the largest space velocities (case 1). The upper limit on the space velocity for this family depends on the mass-radius relationship for massive helium stars. The initial mass of the main-sequence progenitor of a 16 $M_{\odot}$ helium star is about 40 $M_{\odot}$, which is close to the maximum mass of stars that produce neutron stars (van den Heuvel & Habets 1984). The helium star has a radius close to 1 $R_{\odot}$ (Paczyński 1971). The semimajor axis of the semidetached binary, consisting of a 16 $M_{\odot}$ helium star and a neutron star component, is ~ 1.7 $R_{\odot}$. The neutron star has an orbital velocity of ~ 1300 km s^{-1} prior to the second supernova explosion, and its velocity after disruption of the binary is $\sim 81\%$ of the orbital velocity before disruption (Boersma 1961; Tutukov et al. 1984). Thus, the upper limit on the space velocity of the ejected neutron star is about 900 km s^{-1}. But, being a runaway star, the system has a velocity of ~ 100 km s^{-1} before the second supernova explosion (see Figs. 7–9). Therefore, in the binary star scenario, the upper limit on the peculiar space velocity of neutron stars is ~ 1000 km s^{-1}.

It is quite suprising to see in this case good agreement with the observations, in spite of significant uncertainties remaining in pulsar distance scales (Lyne & Lorimer 1994). The upper limit on the observed space velocity distribution is very close to 1000 km s^{-1} (Harrison et al. 1993; Lyne & Lorimer 1994, Fig. 4). This high space velocity is, in our interpretation, a direct consequence of a significant orbital contraction during a second common envelope event.

A second family of fast neutron stars (case 2) is made up of young neutron stars formed in the second supernova explosion in close binaries and of neutron stars formed in the first supernova explosion in binaries which dissolve during the explosion because of a large initial mass ratio. All of these neutron stars have velocities which are very close to their preexplosion orbital velocity (e.g., Tutukov et al. 1984). Since the mass of the second presupernova star is several times larger than the mass of the neutron star component, the velocity of the second neutron star is several times smaller than the velocity of the neutron star formed in the first supernova explosion (see Fig. 10).

The third family of rapidly moving neutron stars (case 3) consists of post–Thorne-Żytkow objects (red supergiants with a neutron star core), which have lost most of their extended envelopes. Accretion of a small fraction of their envelopes is probably sufficient to accelerate their axial rotation to the extent that they become radio pulsars with spin periods less than about 5 s (e.g., Iben et al. 1995b). Precursor systems are accelerated by recoil during the first supernova explosion in the binary. The space velocities of the final neutron stars are therefore comparable to the velocities of the HMXBs and runaway stars which are their precursors.

Members of the last two well-populated neutron star families (cases 4 and 5) have small peculiar velocities. One of the two families (case 4) is the product of supernova explosions of slowly moving single massive stars produced by mergers of components of close binaries with high initial mass ratios in a (first) common envelope stage. Rapidly rotating FK Com giants may be examples of such mergers in low-mass systems (e.g., Bopp & Stencel 1981; Welty & Ramsey 1994).

The most well-populated family (case 5) originates from wide binaries disrupted by the second supernova explosion. The presupernova systems generally have rather large orbital eccentricities, so that their components spend most of their lives near apastron with small kinetic energies. The first supernova explosion leaves the system bound and decreases the eccentricity of the orbit (Hills 1975, 1983). The second supernova explosion usually disrupts the binary, but the orbital motion of the components is so slow that very little is added to the initial low space velocity of the center of the mass of the system. Therefore, the space velocities of the product neutron stars are close to the center of mass velocity of the original system.

In summary, the scenario code produces two quite different populations of neutron stars: fast remnants of close binary evolution (cases 1–3), and slow remnants of the evolution of closer binaries which merge prior to a supernova explosion to form single stars and of wide binaries with noninteracting components (cases 4 and 5). According to the model, the birthrate of the first population is $\sim 0.007\ \mathrm{yr}^{-1}$, and that of the second population is $\sim 0.021\ \mathrm{yr}^{-1}$ (Tutukov & Yungelson 1993).

6. DISCUSSION

In order to compare the model distribution of neutron-star space velocities with observed velocities of radio pulsars, it is necessary to know which neutron stars can be seen as radio pulsars. A strong magnetic field (2×10^8–2×10^{13} G) and a fast rotation rate ($P_{\mathrm{rot}} = 0.0016$–5 s) (Taylor et al. 1993) would seem to be intrinsic properties of all young neutron stars. The Crab pulsar is a representative example, having $B \sim 4 \times 10^{12}$ G, and $P_{\mathrm{rot}} \sim 0.033$ s. The magnetic field is either a result of compression of the presupernova or the result of a dynamo acting in young neutron stars (Gunn & Ostriker 1970). It has traditionally been assumed that the rotation rate of normal radio pulsars is a result of a contraction by a factor of $\sim 10^3$ of a presupernova core at the moment of formation of the neutron star. This decreases the rotational period of the core by a factor of $\sim 10^6$, which would be enough to form a radio pulsar with $P_{\mathrm{rot}} \sim 1$ s if the precollapse rotational period of the core is ~ 10 days. Ruderman (1972) points out that the collapse of a single magnetic white dwarf rotating with a period of 1 yr will produce a very slow rotator. Of course, some magnetic dwarfs rotate with periods shorter than 1 day (Schmidt & Norsworthy 1991), but they may themselves be products of binary evolution, achieving their rotation rates by accretion. In the case of a possible strong interaction between a presupernova core and the extended envelope of a single star (or between this core and a companion in a wide binary) of radius (or orbital separation) $\sim 1000\ R_{\odot}$ and of rotational period about 1 yr, a young neutron star with a rotational period of ~ 300 s may be produced. This is not small enough for the neutron star to be a typical radio pulsar. Thus, in the absence of firm arguments against a slow rotation rate of presupernova cores, one must accept the possibility that neutron stars produced by single stars and by components of wide binaries may not become radio pulsars.

There are two straightforward ways in which high rotation rates can be achieved in components of close binaries. The first is by collapse of the corotating core of a presupernova component of a binary with orbital period less than ~ 10 days; the tidal interaction between binary components is a very efficient way to establish corotation if the components are close enough ($P_{\mathrm{orb}} \leq 10$ days) (Zahn 1975, 1977; Tassoul 1988). The second is by accretion onto an already formed neutron star of mass from a close companion (e.g., Alpar et al. 1982) or from the extended envelope formed by a merger between a neutron star and a companion. The merger product is called a Thorne-Żytkow object (Thorne & Żytkow 1975, 1977; Cannon et al. 1992). To achieve $P_{\mathrm{orb}} \sim 5$ s, a neutron star with a strong magnetic field need accrete only $\sim 2 \times 10^{-6}\ M_{\odot}$ (e.g., Iben & Tutukov 1995, Iben et al. 1995b), and this can be accomplished after only ~ 100–1000 yr of accretion at the Eddington limiting rate.

To estimate the smallest possible rotational period of a young neutron star in a close binary, one may assume that the rotational period of the helium nondegenerate presupernova is the same as the orbital rotational period. The minimum orbital period accessible for a binary containing a detached 4 $M_{\odot}$ helium star with radius $\sim 0.5\ R_{\odot}$ is $P_{\mathrm{orb}} \sim 1.27$ hr (Paczyński 1971). To be disrupted by a supernova explosion, the binary must lose more than a half of its mass (Boersma 1961). Therefore, the mass of the secondary in such a binary must be less than 1.2 $M_{\odot}$, and the secondary evolves into a degenerate dwarf. If collapse reduces the core radius by ~ 1000 times, the neutron star will rotate with a period of ~ 0.005 s.

The observed high transverse space velocity of the Crab pulsar ($\sim 152\ \mathrm{km\ s}^{-1}$) can be explained naturally as a result of binary disruption (Gott et al. 1970; Harrison et al. 1993). There are indications that the mass of emitting gas in the Crab nebula is small ($\sim 1.2\ M_{\odot}$) (MacAlpine & Uomoto 1991), and that the gas is significantly enriched in helium (He/H ~ 3 by number) (Trimble & Woltjer 1971). Part of the hydrogen-rich presupernova matter is distributed around the Crab in a halo (Murdin 1994), and the mass and chemistry of the ejecta suggest that the presupernova in this case was probably once the low-mass ($\sim 4\ M_{\odot}$) helium core of a star of initial mass ~ 13–14 $M_{\odot}$.

In summary, neutron stars formed from single stars and stars in wide binaries are not expected to rotate rapidly enough to be pulsars, whereas neutron stars formed from close binaries (of types 1–3 described in § 5) easily achieve rotation rates characteristic of radio pulsars. It is not excluded that neutron stars belonging to the closest of wide binaries can accrete enough mass and angular momentum from a wind emitted by a red giant companion to evolve into radio pulsars with $P_{\mathrm{rot}} \leq 3$ s. PSR 0820+02 is a possible example (Iben & Tutukov 1995). It is also possible that some of the widest presupernova systems among close binaries have orbital periods which are too long ($P_{orb} \geq 10$ days) for the eventually formed neutron star to be a radio pulsar.

The scenario model distribution of post-binary single neutron stars over their space velocities is shown in Figure 11. It compares favorably with the velocity distribution of nearby ($D \leq 500$ pc) radio pulsars with known proper motions (Fig. 1*b*) when proper motions are combined with distance estimates based on a dispersion measure and the Lyne et al. (1985) Galactic electron-density distribution. The model explains the observed wide dispersion in pulsar space velocities (Fig. 1*a*) as well as the maximum and the average values of the observed distribution of nearby pulsars (Fig. 1*b*).

Another usual "job" for the ad hoc kick is to disrupt close binaries, reducing the duplicity of radio pulsars to a low level. But, since the secondary massive component explodes in a system with a nearly circular orbit and the amount of mass lost exceeds the amount left in two neutron stars, the second supernova explosion itself (without an ad hoc kick) disrupts most close binaries (~94% of them). The remaining ~6% of close binary stars survive as bound systems in which the companion of the neutron star is a degenerate dwarf (73%), a neutron star (20%), or a black hole (7%). The observed duplicity of neutron stars can be significantly reduced if (1) it is taken into account that, due to gravitational wave radiation, the closest binaries eventually merge and (2) it is assumed that presupernova binaries with orbital periods larger than ~10 days cannot produce neutron stars rotating rapidly enough to be radio pulsars (see Figs. 2–6 in Tutukov & Yungelson 1993).

Existing model estimates of the birthrate of binary neutron stars relative to the birthrate of single ones cannot be directly compared with the observed ratio of the number of binary neutron stars to the number of single neutron stars. Of the 558 pulsars in the Taylor et al. (1993) catalog, 24 are members of close binaries, giving a formal number ratio of 0.043. To transform this ratio into a ratio of birthrates, one has to take into account the difference in volumes of space occupied by the two families and the difference in their average lifetimes and possibly also other selection effects. The strength of a pulsar's magnetic field can depend on the amount of matter it has accreted, which can be different for single neutron stars from disintegrated binaries and for those which remain in bound systems (e.g., Bisnovatyi-Kogan & Komberg 1975; Kulkarni 1986). The evolution of the luminosities of single and binary pulsars can therefore also be different, but the nature of this difference is essentially not known. It is known, however, that the median luminosity of binary pulsars in the Galactic disk (see the Taylor et al. 1993 catalog) is about 5 times smaller than the median luminosity of single pulsars. Further, binary pulsars in the catalog have characteristic timescales more than 100 times larger than those of single pulsars. It is worth pointing out that, to disrupt bound double neutron stars with orbital period about 1 day and orbital velocities about 150 km s^{-1} (such systems are predicted by the model with no ad hoc kicks), an ad hoc kick has to exceed ~150 km s^{-1}. But then, if it is assumed to be universal, this kick would also destroy the pulsar distribution for lower values of the peculiar space velocity given by the observations (see Fig. 1) and also predicted by the scenario model without kicks. Thus, the ad hoc kick explanation of neutron star space velocities creates more problems than it solves.

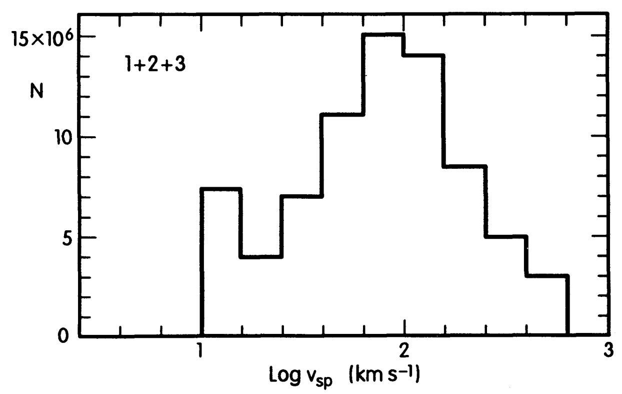

FIG. 11.—The model distribution of Galactic single neutron stars produced by massive close binary stars and Thorne-Żytkow objects (for a Hubble time of 1.5×10^{10} yr).

The scenario code predicts that, in the absence of a kick, about 15% of all young neutron stars are members of wide binaries ($P_{orb} \geq 10^4$ days), having as a companion an OB star (59%), a CO dwarf (39%), or a black hole (2%). The time derivative of the pulsar rotation period can be used to find a very distant companion with an orbital period up to ~20,000 yr (Lamb & Lamb 1976), but no such wide systems are known. Pulsar 1259−63 is in a 1237 day binary with a Be star companion (Phinney & Kulkarni 1994). The orbit is so eccentric ($e = 0.97$) that the progenitor of this system was certainly a rather close binary with about a 10 day orbital period. Therefore, this pulsar could have acquired its rotation during a collapse of the core of a precursor for which $P_{rot} \sim P_{orb}$. Another binary with a rather long orbital period ($P_{orb} \sim 1232$ days) is PSR 0820+02 (Taylor et al. 1993). This pulsar probably acquired its rotation through mass exchange. The low eccentricity of the orbit ($e = 0.01$) is evidence for an efficient interaction between components when the secondary was a giant star (e.g., Iben & Tutukov 1995). Hills (1983) points out that a kick velocity in excess of 100 km s^{-1} would have disrupted this system.

The absence of radio pulsars in wide (noninteracting) and possibly in some wide close binaries is sometimes explained as a consequence of a significant, randomly oriented, natal kick velocity which can disintegrate almost all binaries when the first supernova explosion occurs. Our explanation for wide binaries is that only slowly rotating neutron stars can be formed in them, and that, because of their slow rotation, the neutron stars are not radio pulsars. The scenario model gives a low formation rate for neutron stars in close binaries, but, lacking a model of the evolution of pulsar luminosity with time, this rate cannot be compared directly with the observed duplicity rate to establish either agreement or disagreement.

The magnitude of the ad hoc velocity kick invoked to explain the observed high space velocities of pulsars has grown continuously: 70–100 km s^{-1} (Kornilov & Lipunov 1984), ~90 km s^{-1} (Dewey & Cordes 1987), ~100–200 km s^{-1} (Bailes 1989), ~450 ± 50 km s^{-1} (Lyne & Lorimer 1994), ~480–990 km s^{-1} (Frail, Goss, & Whiteoak 1994). According to Kornilov & Lipunov (1984), a kick of ~100 km s^{-1} is enough to prevent all but a few percent of all neutron stars formed to remain in binaries. The most recent estimates of the kick velocity leave essentially no binary pulsars at all.

Large kicks present a real problem for understanding low-mass X-ray binaries (LMXBs) in globular clusters, where neutron stars must wait billions of years to acquire a close companion and therefore cannot have space velocities in excess of a few tens of km s^{-1}. Furthermore, any universal kick with a velocity larger than a few tens of km s^{-1} would prevent agreement with the observed space velocity distribution of pulsars (Fig. 1), which clearly has a low-velocity ($\lesssim 50$ km s^{-1}) tail.

The birthrate of pulsars given by the "kickless" model scenario is ~ 0.007 yr^{-1}. The uncertainty in this estimate due to uncertainties in the model itself is about a factor of 2. Current semiempirical estimates of the pulsar birthrate are 0.004–0.008 yr^{-1} (Lorimer et al. 1993) and ~ 0.01 yr^{-1} (Narayan & Ostriker 1990). The theoretical space velocity spectrum (Fig. 11), which is in essence the distribution of neutron stars with different space velocities over their birthrate, may legitimately be compared with the observed distribution (Figs. 1*a* and 1*b*) if it is permissible to assume that the lifetime of a pulsar does not depend on its space velocity (see, e.g., Fig. 4). Comparing the scenario model and the observed distributions (Figs. 1, 6, 10, and 11), it is clear that the observed distribution (apart from the large uncertainty associated with the Galactic electron-density distribution) really can be understood as the result of supernova recoil velocities in close massive binaries without the introduction of a significant natal kick of unknown nature. In fact, relying solely on the recoil from symmetric supernova explosions, the scenario model does exactly the job frequently attributed to asymmetric kicks: it produces a population of high-velocity pulsars.

In the scenario model without kicks, it is assumed that supernovae of Type II (SNeII), which are explosions of red supergiants and therefore explosions of single stars or components of wide binaries, produce only slowly rotating neutron stars which are not pulsars. The major parent supernovae for radio pulsars are of type Ib and Type Ic (see Nomoto et al. 1994), and possibly of Type IIb (see Filippenko, Matteson, & Ho 1993). These supernovae are explosions of helium remnants of massive components of close binaries. Possible examples of pulsar producing supernovae are SN 1993J in M81 (Aldering, Humphreys, & Richmond 1994; Utrobin 1994) and SN 1987M (Swartz et al. 1993). The Crab pulsar probably belongs to the same family.

The observed SN Ib to SN II frequency ratio is about 0.27 (Capellaro et al. 1993) or 0.36 (van den Bergh 1991). The scenario model gives 0.35–0.46, depending on the choice of the common envelope parameter $\alpha_{\rm CE}$ (Tutukov, Yungelson, & Iben 1992). Because (in our interpretation) only about one-fourth of all neutron stars produced by supernovae are radio pulsars, and because the beaming factor reduces by several times more the number of observable pulsars, it is predicted that supernova remnants are rarely seen near radio pulsars. A further factor which reduces the probability of coincidences between radio pulsars and diffuse supernova remnants that accompany their formation is the relatively short lifetime of the remnants ($\lesssim 5 \times 10^4$ yr) compared with the average pulsar lifetime (4×10^6 yr). But, progress in the observations of pulsars and of supernova remnants may in the near future provide reliable statistics regarding the connection between young radio pulsars and their related supernova remnants (Frail et al. 1994). It is to be emphasized that a high positional correlation between very young radio pulsars (i.e., those with characteristic times $\gtrsim$20,000 yr) and supernova remnants (Caraveo 1993; Frail et al. 1994) does not imply that a pulsar is formed in every supernova explosion which produces a neutron star. For example, the Type II supernova remnant Cas A, with an age of ~ 300 yr, does not appear to have an associated radio pulsar.

Both observations and the scenario model show that some radio pulsars remain gravitationally bound in a close binary with a neutron star (NS), black hole (BH), or white dwarf (WD) companion. The model shows that the recoil associated with a symmetric supernova explosion is enough to explain the space velocities of these bound systems. The median transverse space velocity of observed binary radio pulsars is ~ 75 km s^{-1} and the scale height of these pulsars is about 600 pc (Phinney & Kulkarni 1994). Hence, these objects have space velocities which are significantly larger than those of their progenitors. For binary pulsars produced by close binaries with interacting components, the scenario model gives $v_{\rm sp} = 40$–150 km s^{-1} (NS + NS), 40–250 km s^{-1} (NS + BH), and 25–150 km s^{-1} (NS + WD) (Tutukov & Yungelson 1993). Thus, the recoil velocities which binary stars acquire during mass loss in symmetric supernova explosions are enough to explain the observed space velocities of binary radio pulsars. The assumption that most radio pulsars are formed in close binaries helps explain the origin of fast pulsars moving toward the Galactic plane from polar directions (Harrison et al. 1993). Examples are PSR 1718−02 ($z = 765$ pc, $v_z = -297$ km s^{-1}) and PSR 0523+11 ($z = -729$ pc, $v_z = -345$ km s^{-1}). During the OB runaway stage, the binary has moved far from the Galactic plane, and the second supernova explosion, disintegrating the binary, sends the two neutron-star remnants off in a direction "opposite" to that of the explosion debris, with the velocity vectors of the neutron stars typically making an angle ψ less than 90°. If the preexplosion orbit is circular, this angle is given by (Gott et al. 1970).

$$\cos \psi = \left[4\left(\frac{M_{\rm ej}}{2M_{\rm NS}}\right)^2 - 3\right]^{-1/2} ,$$

where $M_{\rm ej}$ and $M_{\rm NS}$ are the masses of the debris and of a neutron star, respectively, and $M_{\rm ej} \geq 2M_{\rm NS}$ (to ensure unbinding in the explosion). Since the explosion occurs at a random point in the orbit, the mean direction in which the unbound neutron stars move is arbitrary, but it includes motion back to the plane.

The model predicts that most neutron stars (80% are from single stars or from wide binaries) are formed with low space velocities (Fig. 10, distributions 4 and 5), and this explains why so many neutron stars formed in globular clusters remain there. They are not pulsars at birth, but become so after a capture or exchange collision brings them close to an ultimate mass donor. Since their massive star progenitors are well concentrated toward the central parts of the cluster, they too will be concentrated toward the center. Even some neutron stars formed in close binaries acquire small enough velocities ($\lesssim 20$ km s^{-1} [Fig. 11]) that they can remain in clusters. Those neutron stars which remain in clusters have the opportunity over billions of years to acquire (through two- and three-body interactions) a low-mass companion, pass through a phase as an LMXB, and then evolve into a millisecond radio pulsar (see Bhattacharya & van den Heuvel 1991).

Figures 10 and 11 make it possible to estimate what fraction of all neutron stars formed in our Galacy can leave it after the second supernova explosion in a binary. It is clear that, for the runaway limit velocity of ~ 600 km s^{-1} (Haud & Einasto 1989), only a few percent of all neutron stars formed in our Galaxy can run away from it, forming around the Galaxy an outflowing corona which is being filled with neutron stars at the rate of $\sim 3 \times 10^{-4}$ yr^{-1} (Fig. 11). It is also evident that, because of their smaller gravitational potential, dwarf galaxies and globular clusters can lose a significant fraction of their newly formed neutron stars.

Problems remain that cannot yet be solved. The scenario model finds that $\sim 7\%$ of all neutron stars formed in massive close binary systems remain gravitationally bound with a neutron star, white dwarf, or black hole companion (Table 1 in Tutukov & Yungelson 1993). The observed pulsar duplicity rate for pulsars which are not in globular clusters is about 3% (Taylor et al. 1993). As already discussed, these two percentages cannot be compared directly, since pulsars in binaries and field pulsars have different average characteristics which prevent a straightforward comparison between a ratio of birthrates and a ratio of numbers. To produce theoretical estimates of the observed duplicity of pulsars, a model has to take into account the evolution with time of the luminosities of single and binary pulsars and other selection parameters such as the beaming factor. A model also has to take into account the evolution of neutron stars in binaries (e.g., merging of some of the closest binaries due to gravitational wave radiation). Apart from this, the model has to include the initial distributions of single and binary neutron stars over rotational period and magnetic field strength, and the evolution in time of the magnetic field. All of these parameters, still poorly known, can significantly influence the results of a transformation of the theoretical birthrates into observed numbers of binary and single pulsars. Therefore, the observed ratio of numbers of binary and single pulsars does not serve as a useful constraint on model scenarios.

It is not possible to reject a natal kick entirely. Several mechanisms have been proposed which are reasonable from a physical point of view and have the effect of introducing asymmetry in the supernova explosion (e.g., Chugai 1984; Janka & Müller 1994; Khokhlov 1994; Burrows & Hayes 1995; Burrows et al. 1995) or causing acceleration of a young pulsar (e.g., Harrison & Tademaru 1975; Helfand & Tademaru (1977). A distribution of random, stochastic kicks centered about a mean kick velocity smaller than 10–20 km s^{-1} still remains possible in the framework of the scenario model, as such small kicks will not appreciably alter the velocity distribution predicted for neutron stars produced in close binaries. It could still influence the velocity distribution of neutron stars formed in wide massive binaries, but such neutron stars probably do not become pulsars.

On the other hand, the introduction of randomly oriented kicks with a mean value significantly exceeding 10–20 km s^{-1} is by itself not sufficient to produce agreement with the observed distribution of pulsars for transverse velocities larger than 10–20 km s^{-1} (Figs. 1 and 11). The kicks must also be able to explain the observed velocity dispersion and particularly the upper limit on the velocity. In other words, the kick scenario has to repeat the job which is already done quite naturally in the framework of the scenario model with ordinary supernova recoils, and this canot be done with a larger, randomly oriented kick or a distribution of kicks narrowly centered on a large value such as 450 km s^{-1}.

The role of wide massive binaries in the formation of radio pulsars is not yet clear. Although we have suggested that such binaries do not produce pulsars, the main problem is that we do not know yet from the observations what fraction of pulsars belong to this slow moving family (Figs. 1 and 6). If the fraction is really about a half or even somewhat larger (Fig. 6), there are two possible explanations, each of which introduces new problems. If the low v_t radio pulsars are formed in massive close binaries, it is necessary to introduce an "antikick" to offset the orbital motion of the presupernova in such a way that approximately half of the high-velocity pulsars produced by the scenario model with no kicks is converted into low-velocity pulsars. This solution appears even more arbitrary than the assumption of randomly oriented kicks invoked to produce high-velocity pulsars. If the antikick is unpalatable, one could call upon wide binaries to produce the low-velocity pulsars; being as numerous as they are, wide binaries can easily supply a proper birthrate (see Fig. 10). For example, observed slowly moving pulsars could be the progeny of close binary stars which merge during the first mass-exchange phase (case 4 in Fig. 10), leaving a single star to evolve into a supernova. However, the merger product is expected to evolve in the same way as do massive noninteracting stars in wide binaries. Given the complete absence of pulsars in wide binaries with noninteracting components, it is difficult to argue that the neutron star descending from a merger product should be a rapid rotator. Further, at least 16% of all neutron stars produced by wide binaries are expected to have distant white dwarf or main-sequence companions (Tutukov & Yungelson 1993), and, up to the present, not one example of such a binary has been discovered. Thus, on the premise that all neutron stars are pulsars, one is forced once more to introduce a low-velocity (10–20 km s^{-1}) natal kick, destroying wide binaries at the moment they form neutron stars.

We emphasize that the necessity for such strange solutions arises only if, after a special study of slowly moving radio pulsars which takes the main effects of observational selection into account it is established that the low-velocity pulsar family (see Fig. 6) is well populated. This study is an important observational task, and the result will help clarify the requirements for the formation of radio pulsars.

Single pulsars ejected from close binaries are related to pulsars which remain in close binaries after their formation in the sense that the same mechanisms for spin-up (mass exchange and tidal forces) operate in both cases. In the case of pulsars in binaries, there are clear correlations between $P_{\rm orb}$ and $P_{\rm rot}$ which can be related to accretion from a Roche-lobe overfilling companion (binary millisecond pulsars [MSPs]) or to tidal action which forces the neutron star precursor to rotate synchronously with the orbital period (Iben & Tutukov 1995; Iben et al. 1995b). Further, there appears also to be an inverse correlation between z-height (and therefore space velocity) and $P_{\rm orb}$ for those MSPs in orbits of low eccentricity (Bailes et al. 1994). Such a correlation is expected in the kickless scenario since the recoil from a symmetric supernova explosion is larger the shorter the orbital period. Thus, both the mechanisms which produce observed $P_{\rm rot}$ and the observed correlations between $P_{\rm rot}$, $P_{\rm orb}$, and $v_{\rm sp}$ are understood for binary pulsars in the context of a model in which $v_{\rm sp}$ is due to recoil from a symmetric supernova explosion. Since the orbital characteristics of close binary systems which dissolve during the formation of a neutron star are not unlike those of systems which remain bound, this may be taken as support for the thesis that the space velocities of single pulsars are the result of recoil from a symmetric supernova explosion of a precursor which has been spun up by accretion or by tidal forces.

It is a pleasure to thank Adam Burrows for several very useful comments and suggestions, John Dickel for informative discussions on supernova lore, John Hayes, Lew Snyder, and Doug Swesty for useful discussions on other aspects of the problems addressed here, and the referee for guiding us to the correct description of the kinematics of the neutron stars ejected in a second supernova explosion in a close binary.

REFERENCES

Alderling, G., Humphreys, R. M., & Richmond, M. 1994, AJ, 107, 662
Alpar, M. A., Cheng, A. F., Ruderman, M. A., & Shaham, J. 1982, Nature, 300, 728
Bailes, M. 1989, ApJ, 342, 917
Bailes, M., et al. 1994, ApJ, 425, L41
Bhattacharya, D., & van den Heuvel, E. P. J. 1991, Phys. Rep., 203, 1
Bisnovatyi-Kogan, G. S., & Komberg, B. 1975, Soviet Astron., 18, 217
Blaauw, A. 1961, Bull. Astron. Inst. Netherlands, 15, 265
Boersma, J. 1961, Bull. Astron. Inst. Netherlands, 15, 291
Bonnell, I. A., & Bate, M. R. 1994, MNRAS, 269, L45
Bopp, B. W., & Stencel, R. E. 1981, ApJ, 247, L131
Brown, G. E., & Weingartner, J. C. 1994, ApJ, 436, 843
Burrows, A., & Hayes, J. 1995, in High Velocity Neutron Stars and Gamma Ray Bursts, ed. R. Rothschild & R. Lingenfelter (Washington: AIP), in press
Burrows, A., Hayes, J., & Fryxell, B. A. 1995, ApJ, 450, 330
Burrows, A., & Woosley, S. E. 1986, ApJ, 308, 680
Cannon, R. C., Eggleton, P. P., Żytkow, A. N., & Podsiadlowski, P. 1992, ApJ, 386, 206
Cappellaro, E., Turatto, M., Benetti, S., Tsvetkov, D. Yu., Bartunov, O. S., & Makarova, I. N. 1993, A&A, 273, 383
Caraveo, P. A. 1993, ApJ, 415, L111
Chandrasekhar, S. 1961, Hydrodynamic and Hydromagnetic Stability (New York: Dover)
Chugai, N. N. 1984, Soviet Astron. Lett., 10, 87
Conti, P. S., Leep, E. M., & Lorre, J. J. 1977, ApJ, 214, 759
Cordes, J. M. 1986, ApJ, 311, 183
Dewey, R. J., & Cordes, J. M. 1987, ApJ, 321, 780
Fekel, F. C. 1981, ApJ, 246, 879
Filippenko, A. V., Matteson, T., & Ho, L. C. 1993, ApJ, 415, L103
Frail, D. A., Goss, W. M., & Whiteoak, J. B. Z. 1994, 437, 781
Frail, D. A., & Weisberg, J. M. 1990, AJ, 100, 743
Gies, D. R., & Bolton, C. T. 1986, ApJS, 61, 419
Gott, J. R. 1972, ApJ, 173, 227
Gott, J. R., Gunn, J. E., & Ostriker, J. P. 1970, ApJ, 160, L91
Gunn, J. E., & Ostriker, J. P. 1970, ApJ, 160, 979
Harrington, R. S. 1975, AJ, 80, 1081
Harrison, E. R., & Tademaru, E. 1975, ApJ, 201, 447
Harrison, P. A., Lyne, A. G., & Anderson, B. 1993, MNRAS, 261, 113
Haud, U., & Einasto, J. 1989, A&A, 223, 95
Helfand, D. J., & Tademaru, E. 1977, ApJ, 216, 842
Herant, M., Benz, W., & Colgate, S. 1992, ApJ, 395, 642
Hills, J. G. 1975, AJ, 80, 1075
———. 1983, 267, 322
Iben, I., Jr., & Tutukov, A. V. 1984, ApJS, 54, 335
———. 1995, in Millisecond Pulsars—A Decade of Surprises, ed. A. S. Fruchter, M. Tavani, & D. C. Bacher (ASP Conf. Ser.), 119
Iben, I., Jr., Tutukov, A. V., & Yungelson, L. R. 1995a, ApJS, 100, 217
———. 1995b, ApJS, 100, 233
Isserstedt, J., & Feitzinger, J. V. 1981, A&A, 96, 181
Janka, H. Th., & Müller, E. 1994, A&A, 290, 496
Khokhlov, A. M. 1994, ApJ, 424, L115
Kiseleva, L. S., Eggleton, P. P., & Anosova, J. P. 1994, MNRAS, 267, 161
Kornilov, V. G., & Lipunov, V. M. 1984, Soviet Astron., 28, 402
Kulkarni, S. R. 1986, ApJ, 306, L86
Lamb, D. Q., & Lamb, F. K. 1976, ApJ, 204, 168
Lorimer, D. R., Bailes, M., Dewey, R. J., & Harrison, P. A. 1993, MNRAS, 263, 403
Lyne, A. G., Anderson, B., & Salter, M. J. 1982, MNRAS, 201, 503
Lyne, A. G., & Lorimer, D. R. 1994, Nature, 369, 127
Lyne, A. G., Manchester, R. N., & Taylor, J. H. 1985, MNRAS, 213, 613
Lyne, A. G., & Smith, F. G. 1982, Nature, 298, 825
MacAlpine, G. D., & Uomoto, A. 1991, AJ, 102, 218
Manchester, R. N., & Taylor, J. H. 1981, AJ, 86, 1953
Morris, D., Radhakrishnan, V., & Shukre, C. 1976, Nature, 260, 124
Murdin, P. 1994, MNRAS, 269, 89
Narayan, R., & Ostriker, J. 1990, ApJ, 352, 222
Nomoto, K., Yamaoka, H., Pols, O. R., van den Heuvel, E. P. J., Iwamoto, K., Kumagal, S., & Shigeyama, T. 1994, Nature, 371, 227
Paczyński, B. 1971, Acta Astron., 21, 1
Phinney, E. S., & Kulkarni, S. R. 1994, ARA&A, 32, 591
Popova, E. I., Tutukov, A. V., & Yungelson, L. R. 1982, Ap&SS, 88, 155
Radhakrishnan, V., & Shukre, C. S. 1985, in Supernovae: Their Progenitors and Remnants, ed. G. Srinivasan & V. Radhakrishnan (Bangalor: Indian Acad. Sci.), 155
Ruderman, M. A. 1972, ARA&A, 10, 427
Schmidt, G. D., & Norsworthy, J. E. 1991, ApJ, 366, 270
Shklovski, I. S. 1970, Soviet Astron., 13, 562
Stone, R. S. 1979, ApJ, 232, 520
———. 1982, ApJ, 261, 208
Swartz, D. A., et al. 1993, ApJ, 411, 313
Tassoul, J.-L. 1988, ApJ, 324, L71
Taylor, J. H., & Cordes, J. M. 1993, ApJ, 411, 674
Taylor, J. H., Manchester, R. N., & Lyne, A. G. 1993, ApJS, 88, 529
Thorne, K., & Żytkow, A. N. 1975, ApJ, 199, L19
———. 1977, ApJ, 212, 832
Trimble, V., & Woltjer, L. 1971, ApJ, 163, L97
Tutukov, A. V., Chugai, N. N., & Yungelson, L. R. 1984, Soviet Astron. Lett., 10, 244
Tutukov, A. V., & Yungelson, L. R 1973, Nauch.Inf., 27, 57
———. 1993, Astron. Rep., 37, 411
Tutukov, A. V., Yungelson, L. R., & Iben, I., Jr. 1992, ApJ, 386, 197
Utrobin, V. 1994, A&A, 281, L89
van den Bergh, S. 1991, AJ, 99, 843
van den Bergh, S., McClure, R. D., & Evans, R. 1987, ApJ, 323, 44
van den Heuvel, E. P. J., & Habets, G. M. H. J. 1984, Nature, 309, 598
van den Heuvel, E. P. J., & Heise, J. 1972, Nature, 239, 67
van Oijen, J. G. J. 1989, A&A, 217, 115
Welty, A. D., & Ramsey, L. W. 1994, ApJ, 435, 845
Wielen, R. 1992, in Landolt-Börnstein, Neue Serie, Band 2, Astronomie und Astrophysik, 211
Zahn, J.-P. 1975, A&A, 41, 329
———. 1977, A&A, 57, 383
Zwicky, F. 1957, Morphological Astronomy (Berlin: Springer), 257