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## Letter to the Editor

# Observational constraints on kicks in supernovæ

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**Abstract.** The absence or presence of extremely wide binaries with a radio pulsar and an optical counterpart imposes a strong constraint on the existence and magnitude of kicks in supernova explosions. We search for such systems by comparing the positions of radio pulsars which are not known to be in binaries with the positions of visible stars, and find that the number of associations is negligible. According to the performed population synthesis, this implies that kicks must occur, with a lower limit of at least 10 to 20 km s<sup>-1</sup>.

The single 13-th magnitude star at a distance of 4.9 seconds of arc from the pulsar PSR B1929+10 is a good candidate to be the member of such a wide pair. If it turns out that this pulsar is indeed the member of a wide binary or if another wide pair will be found in the future, the kick-velocity distribution must have a significant contribution from low-velocity kicks.

**Key words:** methods: statistical – catalogs – binaries: general – pulsars: general – pulsars: individual: PSR B1929+10

## 1. Introduction

Neutron stars are believed to receive high velocities upon their formation in a supernova explosion (Gunn & Ostriker 1970). These “kicks” can have a dramatic influence on the evolution of high-mass binaries, preserving binaries which would otherwise be disrupted in the supernova, or splitting binaries which would otherwise remain bound.

There is no direct evidence that kicks happen: they are inferred from e.g. studies of the proper motion of single pulsars (Lyne & Lorimer 1994), fitting observed pulsar characteristics (Hartman 1997), or by explaining a precessing pulsar orbit (Kaspi 1996, see van den Heuvel & van Paradijs 1997, for a brief overview). According to Iben & Tutukow (1996) there are

no kicks at all and pulsars are only formed in type Ib and Ic supernovæ from close interacting binaries see, however, Portegies Zwart & van den Heuvel (1997) for counter arguments.

Our method hinges on the fact that wide binaries are very fragile and therefore sensitive to kicks. Such systems, which are sufficiently detached not to experience a phase of mass transfer, might very well survive the first (and possibly also the second) supernova explosion due to e.g. the primordial eccentricity of the binary, provided kicks are absent (Portegies Zwart & Verbunt 1996). In that case it consists of a radio pulsar in a wide binary with a main-sequence star. Since the components will be widely separated and have small relative orbital velocities, they will be easily mistaken for single stars. Once kicks are considered, however, the survival probability of the binaries is sharply reduced since the relative orbital velocity of very wide pairs is small ( $v_{\text{orb}} \lesssim 1 \text{ km s}^{-1}$ ) compared to the expected average value of kick velocities. Hence, the existence of wide binaries can in principle constrain the validity of kick models. Such systems, if they exist at all, could be identified by searching for positional correlations between radio pulsars and “single” stars. By comparing the expected frequency of such systems with the number identified in catalog comparisons we can ascertain whether kicks play a role, and, if so, place constraints on the lower limit of their velocities.

In the next section we discuss the fraction of such binaries that is expected among radio pulsars. In Sect. 3 we search for positional coincidences between radio pulsars and “single” stars using the Taylor et al. (1993, 1995) catalog and the Hubble Space Telescope Guide Star Catalog (Lasker et al. 1988 and Jenkner et al. 1990). Finally the results are discussed in Sect. 4 and we derive a lower limit to the occurrence of kick velocities.

## 2. The survival of wide binaries

In a binary which is too wide for any Roche-lobe overflow to occur the primary will first explode in a type II or type Ib supernova. A primary with a mass between 8  $M_{\odot}$  and 40  $M_{\odot}$  (van

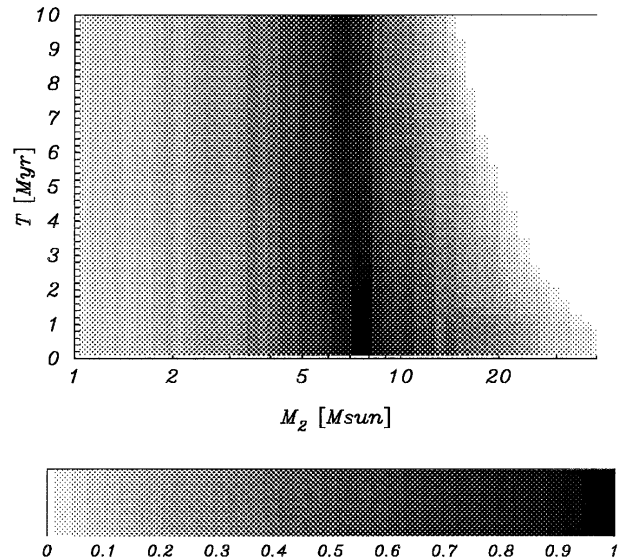
den Heuvel & Habets 1984) is expected to leave behind a radio pulsar. If the binary is eccentric and the eccentricity is conserved until the supernova, the binary has a fair chance to survive and stay bound as a binary with a main-sequence star and a young radio pulsar. However, if there are kicks then the survival probability becomes much smaller. We attempt to model the surviving fraction of wide binaries using the population synthesis model of Portegies Zwart & Verbunt (1996, see also Portegies Zwart & Yungelson 1997)

We assumed the following initial conditions (Abt 1983; Duquennoy & Mayor 1991): the primary mass is chosen from a power-law distribution with an exponent  $\alpha = -2.5$  (Salpeter is  $-2.35$ ) between  $8$  and  $100 M_{\odot}$ . The semi-major axis distribution was taken to be uniform in  $\log a$  ranging from  $a \sim 10 R_{\odot}$  up to  $10^6 R_{\odot}$ . The initial eccentricity-distribution is independent of the other orbital parameters, and is  $\Xi(e) = 2e$ . The mass of the secondary star  $M_2$  is selected with equal probability per mass interval between a minimum of  $0.1 M_{\odot}$  and the mass of the companion star. We limit our study to the binaries which do not experience Roche-lobe contact during their evolution.

We computed models without a kick, with a fixed kick velocity, with a Maxwellian velocity distribution with a three-dimensional dispersion of  $450 \text{ km s}^{-1}$  (which is close to the distribution proposed by Lyne and Lorimer 1995, but with a less pronounced low-velocity tail) and with the distribution proposed by Hansen & Phinney (1996, see also Hartman 1997), which is currently most favored. Note that the revised velocity distribution from Hansen & Phinney (1997) has a smaller contribution from low velocities. Kicks are, when implied, applied in a random direction. Only a binary that survives the first supernova and of which the optical star is still visible can be identified as a radio pulsar with a stellar companion. Whether or not the binary is still detectable depends on a number of details: the time left before the second supernova, the age of the pulsar and the mass of its companion.

For instance, a primary with a mass of  $12 M_{\odot}$  has a stellar lifetime of  $\sim 20 \text{ Myr}$ . If the companion has a mass of  $10 M_{\odot}$ , and therefore has a stellar lifetime of  $\sim 28 \text{ Myr}$ , then the pulsar is observable with a  $10 M_{\odot}$  companion for  $8 \text{ Myr}$ . If the companion mass was much smaller, say  $3 M_{\odot}$ , the pulsar will die long before the companion burns up.

In the model computations the observable lifetime and the initial conditions result in the probability distribution for a range of secondary masses against the age of the pulsar. The model computations reveal (see Fig. 1) that the most likely companion of a young pulsar is a  $7 M_{\odot}$  or  $8 M_{\odot}$  star. This probability drops for lower mass companions; a binary with a small companion mass is more likely to be dissociated in the supernova event. Also for higher mass companions the probability drops, but now it is mainly the initial mass function in combination with the mass-ratio distribution which causes this effect. The effect of the shorter lifetime of the companion star is observable at the high-mass end of Fig. 1; an older pulsar is less likely to have a massive companion.



**Fig. 1.** The probability distribution for secondary mass  $M_2$  (X-axis) of a binary as a function of the age of its pulsar companion (Y-axis) for the model without a kick. Darker shades indicate a higher probability (see lower panel for the scaling). The distributions for the models with kicks have similar shapes, except that the total probabilities decrease.

### 3. Catalog comparison

For each known radio pulsar with a well-determined position, we have looked for a counterpart by correlating the pulsar position with an optical catalog. The known pulsar population is biased due to various selection effects, such as the predominance of sources discovered by Arecibo. But there is no selection effect against finding pulsars in wide binaries because they behave exactly as if they were isolated.

The recently published pulsar catalog contains 706 pulsars (Taylor et al. 1993, 1995). However not all of these pulsars can be considered in our study. All pulsars which are member of a globular cluster are excluded; the evolutionary histories of binaries in globular clusters is very different from those in the galactic disk. Also the pulsars which are known to be the member of an interacting binary system and those which lie in external galaxies are excluded from consideration, such as PSR B1259–63 which has experienced a phase of mass transfer. From the remaining sample, we rejected the pulsars with positional accuracies worse than 1 arcsecond and PSR J0633+1746 (Geminga) of which the distance is not known. The distance to each of the remaining 307 pulsars used for the final analysis is derived from the dispersion measure using the Taylor & Cordes (1993) model for the electron density in the Galaxy and the age obtained from the spin-down rate (Taylor et al. 1995).

The positions from the remaining pulsars are correlated with the Guide Star Catalog, containing 19 million objects of which more than 15 million are stars. This is the largest optical catalog available but has no distance information and the position accuracy is a few tenth of an arcsecond. The completeness limit of this catalog is not uniform over the whole sky but it is lower in more crowded fields. We estimate the local completeness limit

**Table 1.** The radio pulsars which have an optical counterpart in the Guide Star Catalog with a separation (assuming that both objects are at the distance of the pulsar) smaller than 0.1 pc. The first column lists the pulsars followed by the derived distance (in kpc), the angular distance of the optical counterpart (in seconds of arc) and the minimum separation  $d_{\min}$  (in parsec). The last column gives comments about the pulsars' counterpart, whether it is a single star, a multiple star or a single non-stellar object.

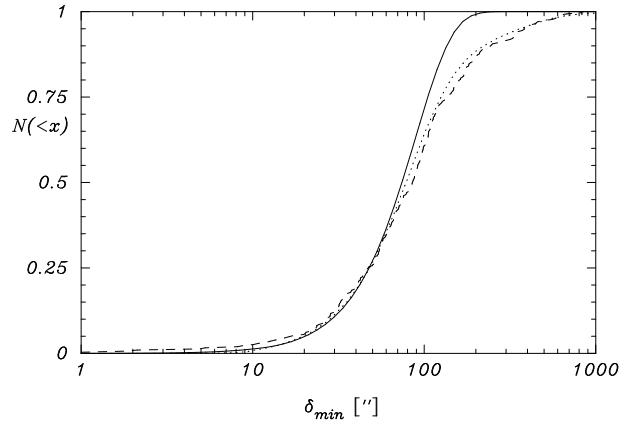
PSR	$r_{\text{psr}}$ [kpc]	$\delta_{\min}$ ["]	$d_{\min}$ [pc]	Comment
B0454+55	0.79	15.42	0.059	multiple star
B0819+74	0.31	26.12	0.039	multiple star
B0950+08	0.12	116.60	0.068	single star
B1650-38	5.12	2.12	0.053	single star
B1822-09	1.01	12.70	0.062	single non-star
B1839+09	2.49	1.82	0.022	single non-star
B1929+10	0.17	4.87	0.004	single star
B1951+32	2.5	8.16	0.099	single non-star

by counting the number of stars as a function of their magnitude (within bins of half a magnitude) within a circle of one degree radius around the position for each pulsar. The local limit was estimated to be half a magnitude less than the magnitude bin with the maximum number of stars.

After completing the correlation, each pulsar is assigned its nearest optical neighbor from the Guide Star Catalog with a given angular separation  $\delta_{\min}$ . This angle is converted into a lower-limit for the true separation in parsec between the pulsar and the optical counterpart  $d_{\text{psr}}$ , using the estimated distance to the pulsar  $r_{\text{psr}}$ . A separation larger than 0.1 pc between the pulsar and its optical “counterpart” indicates that the pulsar and the star cannot be associated. Binaries with major axes larger than  $\sim 0.1$  pc will be dissociated easily by a hard encounter of a neighboring star or passing giant molecular clouds (Binney & Tremaine 1987). Note that this separation is rather uncertain.

Table 1 gives a list of the pulsars which are associated with an optical counterpart with a minimum separation of  $< 0.1$  pc. The pulsars which have a non-stellar object as an optical counterpart are not considered in our analysis. Those which correlate with a multiple star may be of interest but we neglect them here because our model computations do not incorporate triples. Pulsar PSR B0950+08 is most likely not associated with its single star counterpart. It is statistically not unlikely to find a counterpart at such an angular distance  $\delta_{\min}$ . The visual magnitude of the optical counterpart of PSR B1650-38 is  $11^m.6$  and at the distance of the pulsar (5.12 kpc) a  $\sim 15M_{\odot}$  star could be hidden without being noticed. At the age of the pulsar of 1.7 Myr it is rather unlikely to have such a massive companion (see Fig. 1). The pulsars PSR B1929+10 has an optical counterpart with a magnitude of 12.9 with a minimum separation of 0.004 pc and is therefore a good binary candidate. The high proper motion of PSR B1929+10 of about 100 mas/yr (see Taylor et al. 1995) makes it possible to test its counterpart for binarity.

Fig. 2 gives the cumulative distribution of angles between 307 radio pulsars and their nearest entry in the Guide Star Catalog. The expected distribution (solid line) of smallest angles



**Fig. 2.** Cumulative distribution of the closest distance between a pulsar and its nearest star in arcseconds. The dashed line gives the results for the correlation between 307 pulsars with the Guide Star Catalog. The solid line is the theoretically expected distribution for the smallest angle between nearest neighbors a set of 19 million isotropically distributed objects on the sky. The dotted line gives the cumulative nearest neighbor distribution of about 30000 randomly selected single stars in the Guide Star Catalog. A Kolmogorov-Smirnov test reveals that the nearest neighbor distribution for radio pulsars (dashed) and the randomly selected entries in the Guide Star Catalog (dots) are not distributed differently with a confidence level of 98.7%.

assumes that stars and pulsars are distributed isotropically on the sky. The deviation of the observed distributions indicates that pulsars and stars are not distributed isotropically; radio pulsars and single stars are confined to low Galactic latitude.

#### 4. Comparison of the model results with the observations

Comparison of the pulsar catalog with the Guide Star Catalog provides the following information for each pulsar: The distance to the sun (determined from the dispersion measure), the age (derived from the pulse period and its derivative), the magnitude limit of the Guide Star Catalog in the direction of the pulsar and the angular distance between the pulsar and the nearest neighboring star  $\delta_{\min}$ .

The distance to each radio pulsar  $r_{\text{psr}}$  together with the local magnitude limit of the Guide Star Catalog in the direction of the pulsar is used to derive the maximum absolute magnitude for a companion of the pulsar which should have been noticed. The transformation from this relative magnitude limit  $m_v$  to the absolute magnitude  $M_v$  is performed using the following relation:  $m_v - M_v = 5 \log r_{\text{psr}} - 5 + Ar_{\text{psr}}$  where we used  $A = 1.6 \text{ mag kpc}^{-1}$  to correct for interstellar extinction and  $r_{\text{psr}}$  in kpc. (Note that an extinction of  $A = 1.6 \text{ mag kpc}^{-1}$  is rather high for objects which have a large scale height above the galactic plane, but we are interested in lower limits to the observability of companion stars.)

Using the absolute magnitude limit for each pulsar together with a mass-luminosity relation for zero-age main-sequence stars provides a *minimum* mass of a main-sequence star  $m_{\min}$  which could have been seen at the distance of this pulsar.

**Table 2.** The probabilities for the set of observed pulsars to have a companion which should have an entry in the Guide Star Catalog. The first row gives the value of the fixed velocity kick in km/s and the distribution proposed by Hartman (1997, see also Hansen & Phinney 1996) for the ninth column ( $f_H$ ) and a Maxwellian ( $f_M$ ) with a dispersion of  $450 \text{ km s}^{-1}$  for the last. The second and third row give the expectation values  $E$  for the computations with 100% and  $\sim 50\%$  binarity, respectively, for the total number of expected binaries found.

$v_k$	0	1	5	10	15	20	25	$f_H$	$f_M$
100%	52	40	11	3.2	1.2	0.45	0.17	0.32	0.01
50%	26	20	5.6	1.6	0.59	0.23	0.09	0.17	0.00

We compute the probability  $P_b$  that a pulsar has retained its companion and that this star is still visible. This  $P_b$  is obtained by integrating in Fig. 1 from  $m_{\min}$  to the maximum companion mass at the age of the pulsar with a binwidth of 1 Myr.

The model computations provide us with the number of single pulsars from dissociated binaries  $N_s$  and pulsars which are still member of a binary after the first supernova  $N_b$ . For  $N_b$  we only selected those pulsars with a major axis large enough that no Roche-lobe overflow occurred and small enough that the binary is not dissociated by a close encounter in the Galactic plane, i.e. between  $\sim 10^4 R_\odot$  and 0.1 pc. Binaries with smaller and larger major axes fall beyond the scope of this discussion.

or simplicity we assume 100% binarity among the progenitors but we also perform computations with 50% binarity (see Table 2). For each individual pulsar we can now compute the expectation value  $E_{\text{obs}}$  that it has an observable companion by correcting  $P_b$  for the fraction of pulsars in binaries:

$$E_{\text{obs}} = P_b \frac{N_b}{N_s + N_b}. \quad (1)$$

The total expected number of optical counterparts among radio pulsars which should have an entry in the Guide Star Catalog is given by:

$$E = \sum_i^{N_{\text{psr}}} (E_{\text{obs}})_i, \quad (2)$$

where the sum goes over all selected radio pulsars  $N_{\text{psr}} = 307$  in the catalog. A value of  $E$  larger than unity indicates that we expect to see at least one binary among the observed radio pulsars. Table 2 gives this probability for the various models. The pulsars distances are uncertain with a factor of two or so, but our results are not very sensitive to the distance scaling. If the distances to the pulsars are increased with a factor of two low mass companions become hard to observe but the probability for having such a companion is small anyway (see Fig. 1).

## 5. Conclusion

Comparison of the positions of 307 known radio pulsars on the sky with those of visible stars reveals that a tiny fraction of the radio pulsars can be associated with an entry in the Guide Star Catalog. The associated fraction is considerably smaller than

what is expected on statistical grounds if there are no kicks. An asymmetry in all supernovæ of at least 10 km/s satisfactorily explains this underabundance of optical counterparts. This is in agreement with the results of Cordes & Chernoff (1997) who find no evidence for a low velocity tail. The kick velocity distribution proposed by Hansen & Phinney (1996) and Hartman (1997) is also sufficient to explain this lack. However, if the possible counterparts found in this paper are indeed associated with a radio pulsar the kick-velocity distribution requires a contribution from velocities below  $\sim 10 \text{ km s}^{-1}$  and provides evidence for the presence of a low-velocity tail.

If this kick-velocity distribution represents indeed the intrinsic velocity kick received by neutron stars, the observed number of single radio pulsar should be at least a factor 3 larger than at present before one can hope to find a very wide binary which contains a radio pulsar.

The only pulsar which is possibly a member of a very wide binary is PSR B1929+10. Its companion could be a  $2 M_\odot$  main-sequence star at the distance of the pulsar.

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