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INTRINSIC KICKS AT BIRTH ARE REQUIRED TO EXPLAIN THE OBSERVED PROPERTIES OF SINGLE AND BINARY NEUTRON STARS

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ABSTRACT

The single assumption that neutron stars receive a kick velocity at their formation explains a large variety of observations, ranging from observed properties of individual binary radio pulsars and Be/X-ray binaries to the observed birth rates and dynamical properties of the populations of low-mass X-ray binaries and recycled radio pulsars. The rejection of this one assumption by Iben & Tutukov compels them to introduce a considerable number of ad hoc hypotheses, each explaining a only small part of the observational results. We conclude that the choice of the single powerful assumption that neutron stars receive a kick velocity at their formation is highly preferable.

Subject headings: pulsars: general — stars: kinematics — stars: neutron — stars: statistics

1. INTRODUCTION

In a recent paper Iben & Tutukov (1996) have argued that the very broad space velocity distribution of radio pulsars (mean velocity, as estimated by Lyne & Lorimer 1994, of 450 km s^{-1}) can be explained by the disruption of binary systems and does not require intrinsic kicks imparted to the star during the collapse event in which the neutron star was born. The latter mechanism had been originally suggested by Shklovskii (1970). In the last decade several arguments in favor of this idea have been put forward (see, e.g., Dewey & Cordes 1987; Brandt & Podsiadlowski 1995).

In order to explain all the observed space velocities of pulsars by binary disruption, Iben & Tutukov (1996) have to replace one single ad hoc assumption (i.e., intrinsic kicks are imparted during collapse) by at least four other ad hoc assumptions, which are explicit and implicit in their paper, as follows:

1. Single stars and components of wide (i.e., noninteracting) binary stars do not leave radio pulsars (i.e., they leave only neutron stars that spin slowly, $P > 5$ s).
2. Only helium stars in close binaries and exotic objects (e.g., Thorne-Żytkow stars) leave neutron stars spinning with periods sufficiently short to make them observable as radio pulsars.
3. The birth properties of pulsars can be derived from only the local pulsar population within 500 pc from the Sun.
4. The birth rate of low-mass X-ray binaries is orders of magnitude higher than observed but nature hides most of them.

We will not address here the issue whether, in case one can explain a wide variety of observational facts by introducing only one ad hoc assumption, one should prefer to replace this one assumption by a considerable number of other assumptions, in order to explain these same observations. Occam's razor would suggest that the first approach is to be preferred (see Derks 1993 for a recent discussion of this sharp instrument, the use of which can be traced back to Aristotle). Instead of discussing this question, we rather choose in this paper to list the arguments derived from the observations—many of them compelling—which indicate that indeed intrinsic velocity kicks are imparted to neutron stars at birth.

Before this, we wish to point out that in their analysis Iben & Tutukov attempt to correct for the selection effect against distant low-velocity pulsars by dividing their local surface density by v_t^2 (v_t is the pulsar's transverse velocity); this results in a very high peak in the distribution at low velocities. Many of the arguments in Iben & Tutukov's paper are based on this peak. From an extensive study of basically the same pulsar proper motion data, in which great care was taken to correct for all relevant selection effects (including those considered by Iben & Tutukov), Hansen (1996) finds no evidence for a low-velocity peak in the pulsar velocity distribution. On the other hand, according to his analysis, the mean velocities at birth are 250–300 km s^{-1} rather than the 450 km s^{-1} found by Lyne & Lorimer (1994).

2. OBSERVATIONAL EVIDENCE FOR KICKS

2.1. *Nonalignment of Spin and Orbit in PSR J0045−7319*

In the binary radio pulsar PSR J0045−7319, which is a member of the SMC, a neutron star is in orbit around an early B star. The rotation axis of the B star is misaligned with the normal on the orbital plane, as is evidenced by the precession of the orbital plane (Kaspi et al. 1996). The B star was the mass-gaining component during the phase of mass transfer that preceded the current phase in the evolution of this system. The large amount of mass that the B star received from its companion through an accretion disk must have caused its rotation axis to have been aligned with the normal on the orbital plane, prior to the supernova (SN) explosion that created the pulsar. Its present misalignment indicates a kick velocity component imparted to the neutron star perpendicular to the orbital plane. The imparted kick is estimated to be at least 100 km s^{-1} (Kaspi et al. 1996). In addition, the B star in this system appears to be rotating retrogradely with respect to the orbital motion, as is inferred from the very large rate of decrease of its orbital period (Lai 1996). Such retrograde rotation can be explained only by a retrograde kick velocity imparted to the neutron star at its birth (Lai 1996). This is because—due to tidal interaction—the components of the close progenitor

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system of this binary will, prior to the supernova, certainly have been in prograde rotation.

2.2. *Orbital Eccentricities of B-Emission X-Ray Binaries*

As large-scale mass transfer from a Roche lobe–filling companion took place in these systems before the SN explosion, the orbits of the systems before the explosion are expected to have been tidally circularized prior to the explosion. In order to explain the presently observed large eccentricities, intrinsic kicks are required, as was shown by van den Heuvel (1994) and Verbunt & van den Heuvel (1995). The argument is simple: the exploding stars in most of these systems were helium stars of rather low mass, in the range 2.5–3.0 $M_\odot$. It is easy to show (see, e.g., the expressions given by Hills 1983) that in such a situation with an initially circular orbit, the orbital eccentricity imparted by a symmetric SN explosion of the helium star will always be less than 0.15 (assuming a neutron star mass 1.45 $M_\odot$). The observed eccentricities of Be/X-ray binaries and binary pulsars with a B-type companion are typically in the range from 0.3 to 0.9, which can be obtained only if considerable kick velocities are imparted to the neutron stars at birth. Table 1 shows the minimum kick velocities required to be imparted in order to obtain the observed eccentricities of these Be/X-ray binaries (cf. van den Heuvel 1994).

2.3. *The Low Incidence of Double Neutron Stars in the Galaxy*

Population synthesis calculations in which binary evolution is included and in which supernovae are assumed to explode symmetrically (no kicks) always result in a high birth rate of close double neutron stars, of order several times 10^{-4} yr^{-1} in the Galaxy (Clark, van den Heuvel, & Sutantyo 1979; Dewey & Cordes 1987; Meurs & van den Heuvel 1989; van den Heuvel 1992; Tutukov & Yungelson 1993). However, the birth rate derived from observations is very much smaller and certainly not larger than 10^{-5} yr^{-1} (Phinney 1991; Narayan et al. 1991; van den Heuvel & Lorimer 1996).

It has been argued that the double neutron star systems are abundant, but rarely observed, because in most of them the pulsars would have strong magnetic fields and therefore they would be short-lived. However, Bailes (1996) showed that the absence of close double neutron stars with a normal (strong magnetic field) pulsar among the $\sim$700 known normal (nonrecycled) pulsars that are presently known implies that the birth rate of double neutron stars, even those with strong magnetic fields, is less than 1.6×10^{-5} yr^{-1}. Otherwise, by now at least one close binary neutron star with a strong-field (nonrecycled) pulsar should have been found. (It was pointed out to us by R. Wijers that PSR B2303+46 may be one such unrecycled pulsar.)

All population evolution models with symmetric supernovae produce birth rates some 1–2 orders of magnitude larger than observed (see above), whereas simulations which include kicks of a few hundred km s^{-1} produce the correct birth rates (cf. Spreeuw & Portegies Zwart 1995; Lipunov et al. 1996; Bagot 1996). Therefore, there seems no way to evade the conclusion that kicks are required to explain the observed double neutron star birth rate.

TABLE 1

Orbital Parameters of Be/X-Ray Binaries

Be/X-Ray Binary	P_{orb} (days)	e	Required Velocity (km s^{-1})
A0538−66..........	16.7	>0.4	>80
A0115+63..........	24.3	0.34	>60
V0332+53..........	34.3	0.31	>50
A0535+26..........	111.0	0.30	>32
PSR 1259−63......	3 yr	0.87	>200

2.4. *The Low Incidence of Low-Mass X-Ray Binaries in the Galaxy*

Low-mass X-ray binaries (LMXBs) are thought to originate from binaries with components that differ very much in mass, i.e., consisting of a star of $M \geq 10$ $M_\odot$ and a star ≤ 1 $M_\odot$. Such systems evolve through a common-envelope (CE) phase, resulting in a close system consisting of the helium core of the massive star, together with a low-mass star (≤ 1 $M_\odot$). When the helium star explodes, a close system of a neutron star and a low-mass companion results that later on evolves into an LMXB. In view of the steepness of the initial mass function, most systems will originate from primaries in the mass range 10–15 $M_\odot$, which leaves helium stars in the range 2.5–4 $M_\odot$. If we assume that the neutron stars have a mass $M = 1.45$ $M_\odot$, in a symmetric SN, all systems with a 1 $M_\odot$ companion and a helium star less than 3.9 $M_\odot$ will lose less than half the system mass in the SN and, therefore, will remain bound if the SN is symmetric. This results in a high galactic birth rate of LMXBs, of order greater than 10^{-4} yr^{-1} (Iben & Tutukov 1995). On the other hand, the birth rate of LMXBs as derived from the observations is in the range 10^{-6} to at most 10^{-5} yr^{-1} (if it were larger, far more LMXBs should be observable than the $\sim$100–200 found in the Galaxy; see, e.g., van Paradijs 1995). Again, the only way to explain consistently this low birth rate is by the existence of kicks of a few hundred km s^{-1} imparted to the neutron stars at birth. Such kicks are also required to explain the space velocity and z distributions of the LMXBs, which cannot be obtained without them (van Paradijs & White 1995; Brandt & Podsiadlowski 1995; Bhattacharya & Ramachandran 1996).

3. CONCLUSION

The single assumption that neutron stars receive a kick velocity at their formation turns out to be a powerful one. It explains a large variety of observations, ranging from observed properties of individual binary radio pulsars and Be/X-ray binaries to the observed birth rates and dynamical properties of the populations of LMXBs and recycled radio pulsars. Rejection of this one assumption necessitates the introduction of a considerable number of ad hoc hypotheses, each explaining a only small part of the observational results. To us, choosing the single powerful assumption is highly preferable, and we conclude that neutron stars receive a kick velocity at their formation.

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