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The Formation of the Most Relativistic Pulsar PSR J0737−3039

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Abstract. We present an updated set of constraints for the progenitor of PSR J0737−3039 and for the natal kicks imparted to pulsar B taking into account both the evolutionary and kinematic history of the double neutron star. For this purpose, we use recently reported scintillation velocity measurements to trace the motion of the system in the Galaxy backwards in time as a function of the unknown orientation Ω of the systemic velocity projected on plane of the sky as well as the unknown radial velocity V_r. The absolute limits on the orbital separation and the mass of pulsar B's helium star progenitor just before its supernova explosion are $1.2\,R_\odot \lesssim A_0 \lesssim 1.7\,R_\odot$ and $2.1\,M_\odot \lesssim M_0 \lesssim 4.7\,M_\odot$. The kick velocity is constrained to be between $60\,\mathrm{km\,s^{-1}}$ and $1660\,\mathrm{km\,s^{-1}}$ and to be misaligned from the pre-SN orbital angular axis (which could be associated with pulsar B's spin axis) by least 25° . We also derive probability distribution functions for the kick velocity imparted to pulsar B and for the misalignment angle between pulsar A's spin and the post-supernova orbital angular momentum for both isotropic and polar kicks. The most probable values of both quantities depend sensitively on the unknown radial velocity. In particular, tilt angles lower than 30°–50° tend to be favored for current radial velocities of less than $\simeq 500\,\mathrm{km\,s^{-1}}$ in absolute value, while tilt angles higher than 120° tend to be associated with radial velocities in excess of $\simeq 1000\,\mathrm{km\,s^{-1}}$ in absolute value.

1. Introduction

The recent discovery of the strongly relativistic binary pulsar (Burgay et al. 2003) which is also the first eclipsing double pulsar system found in our Galaxy (Lyne et al. 2004) has resparked the interest in the evolutionary history and formation of double neutron star (DNS) systems (Willems & Kalogera 2004; Dewi & van den Heuvel 2004; Willems, Kalogera & Henninger 2004). According to the standard formation channel for DNS binaries (e.g. Bhattacharya & van den Heuvel 1991), their progenitors evolve through a high-mass X-ray binary phase where the first-formed NS accretes matter from the wind of a high-mass companion. When the latter fills its Roche lobe, the extreme mass ratio triggers the formation of a common envelope which extracts orbital energy and angular momentum and causes the NS and donor core to spiral-in towards each other. If the inspiral can be stopped before the components coalesce, a tight binary is formed consisting of the first-formed NS and a helium star companion. After it exhausts its central helium supply, the helium star expands and a second, this time stable, mass-transfer phase is initiated which spins the NS up to millisecond periods. At the end of the mass-transfer phase the helium star's core explodes and forms the second NS.

In this paper, we present constraints on the properties of the progenitor of PSR J0737−3039 just before the supernova (SN) explosion that gives birth to pulsar B. In view of the recent scintillation velocity measurements, which were first presented at the meeting (Ransom et al., in this volume) and updated shortly thereafter (Ransom et al. 2004), we update our results presented at the conference and account for the system's full kinematic history since the time of its formation. We furthermore present probability distribution functions (PDFs) for the kick velocity imparted to pulsar B and, in reply to the call for theorists' predictions on PSR J0737−3039, we predict the most likely misalignment angle between pulsar A's spin and the post-SN orbital angular momentum as a function of V_r.

2. Progenitor Constraints

In order to derive constraints on the pre-SN binary parameters and the kick imparted to pulsar B, we first use the scintillation velocity components determined by Ransom et al. (2004) to trace the Galactic motion of the system backwards in time as a function of the unknown orientation Ω of the scintillation velocity in the plane of the sky and the unknown radial velocity V_r. Assuming that the system is at most 100 Myr old, we find that it may have crossed the Galactic plane twice in the past. Identifying these plane crossings with possible birth sites yields estimates for the age and post-SN peculiar velocity which are shown in Figure 1 as a function of Ω and V_r. If the system has crossed the Galactic plane only once in the past, there is a wide range of Ω- and V_r-values for which PSR J0737−3039 may be remarkably young ($\lesssim$ 20 Myr). If, on the other hand, the system has crossed the Galactic plane twice, it is at least 20 Myr old regardless of the values of Ω and V_r. The peculiar velocity right after the formation of pulsar B may furthermore be anywhere between $\simeq 90\,\mathrm{km\,s^{-1}}$ and $\simeq 1200\,\mathrm{km\,s^{-1}}$.

Next, we determine the post-SN orbital parameters for each possible birth site by integrating the equations governing the orbital evolution due to gravitational radiation backwards in time up to the age corresponding to that birth site. These post-SN binary parameters are related to the pre-SN parameters and to the kick magnitude and direction by the conservation laws of orbital energy and angular momentum. The requirements that (i) the solutions to these relations must be real, (ii) the binary components must remain bound after the SN explosion, (iii) the post-SN orbit must pass through the position of both stars at the time of the SN explosion, and (iv) the kick must produce the right post-SN peculiar velocity, then impose constraints on the pre-SN orbital separation and on the mass of pulsar B's helium star progenitor as well as on the magnitude and direction of the kick imparted to pulsar B (for more details, see Willems et al. 2004, and references therein).

Regardless of the values of the two unknown parameters Ω and V_r, the pre-SN orbital separation is constrained to the interval between $1.2\,R_\odot$ and $1.7\,R_\odot$. For these tight constraints, the system is able to avoid Roche-lobe overflow prior to the formation of pulsar B only if the mass of B's helium star progenitor is higher

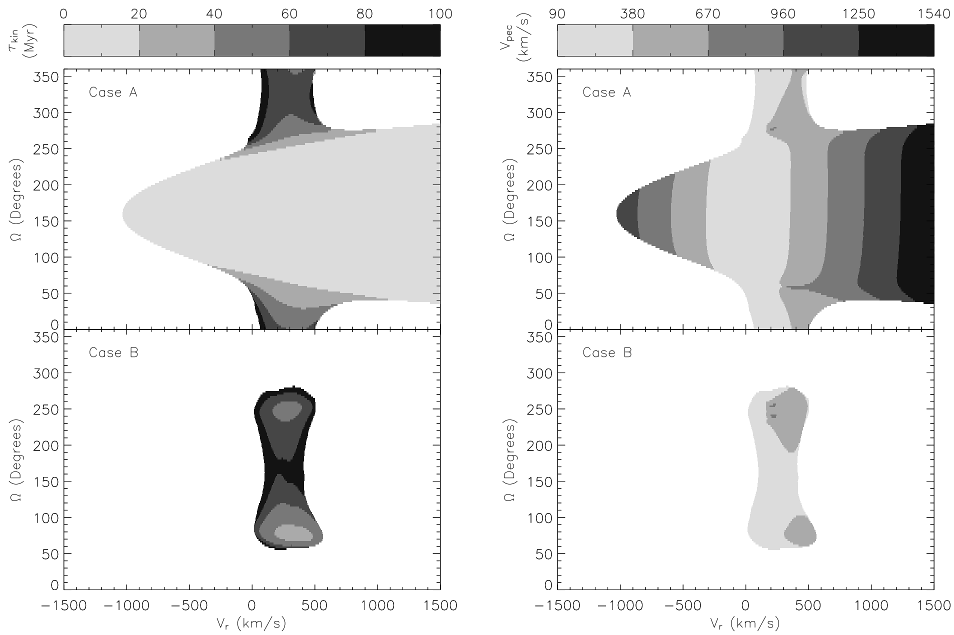

Figure 1. Kinematic age $\tau_{\rm kin}$ (left) and post-SN peculiar velocity $V_{\rm pec}$ (right) of PSR J0737−3039 as a function of Ω and V_r. Cases A and B respectively refer to the first and second Galactic plane crossing when following the orbit of the system backwards in time.

than $25\,M_\odot$ and if the kick velocity imparted to pulsar B at birth was larger than $\simeq 1200\,{\rm km\,s^{-1}}$. Helium stars of such a high mass are not only very unlikely (due to the strong wind mass loss), they are also expected to end up as a black hole instead of a NS. The pre-SN binary therefore most likely consisted of the first-formed NS in orbit around a Roche-lobe filling helium star (see also Dewi & van den Heuvel 2004). We constrain the mass of the latter to be between $2.1\,M_\odot$ and $4.7\,M_\odot$, where the lower mass limit corresponds to the smallest mass for which a single helium star is expected to form a NS and the upper limit to the highest mass for which mass transfer onto the first-formed NS is expected to be dynamically stable (Ivanova et al. 2003). The lower limit of $2.1\,M_\odot$ furthermore implies that a birth kick with a velocity of at least $60\,{\rm km\,s^{-1}}$ was imparted to the second-born NS, in agreement with the minimum kick velocity derived by Willems & Kalogera (2004) and Dewi & van den Heuvel (2004). From the condition that the binary must remain bound after the second SN explosion, we also derived an upper limit for the kick velocity of $1660\,{\rm km\,s^{-1}}$. The direction of the kick is constrained to always make an angle of at least 115° with the helium star's pre-SN orbital velocity, and and angle of at least 25°–30° with the pre-SN orbital angular momentum axis (which could be associated with pulsar B's spin axis). Hence, the kicks are generally directed opposite to the orbital motion and could not have been too closely aligned or anti-aligned with the pre-SN orbital angular momentum.

For specific values of Ω and V_r, the progenitor and kick velocity properties often become much more constrained than the absolute limits mentioned above. In

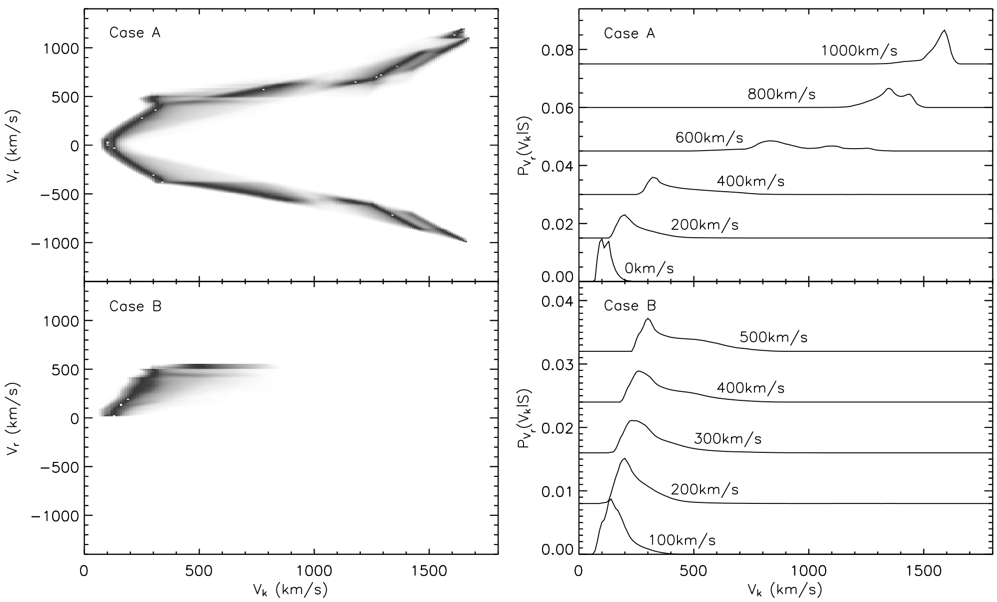

Figure 2. Kick probability distribution functions for PSR J0737−3039B. Left panel: PDFs associated with all admissible V_r-values. The gray scale is linear and varies from light to dark gray with increasing PDF-values. Right panel: PDFs associated with some specific V_r-values (offset by an arbitrary amount).

particular, the condition that the kick must match the post-SN peculiar velocity associated with the considered values of Ω and V_r narrows the range of possible kick velocities to an interval that is about $\simeq 500\,\mathrm{km\,s^{-1}}$ wide. The minimum kick velocity and the tendency of the kick to be directed opposite to the pre-SN orbital motion furthermore increase with increasing absolute values of the radial velocity. For a detailed representation of the progenitor and kick constraints as a function of Ω and V_r, we refer to Willems et al. (2004).

3. Isotropic Kick-Velocity and Spin-Tilt Distributions

Following the procedure described in detail in Willems et al. (2004), we derive probability distribution functions (PDFs) for the kick velocity V_k imparted to pulsar B at birth and for the misalignment angle λ between pulsar A's spin and the post-SN orbital angular momentum under the assumption that all kick directions are equally probable. The PDFs are first derived for all admissible values of Ω and V_r, and next integrated over all possible Ω-angles assuming a uniform distribution between 0 and 2π. The resulting PDFs are shown in Figures 2 and 3 as functions of the remaining unknown parameter V_r.

The kick-velocity distributions exhibit a single peak at kick velocities which increase from $\simeq 100\,\mathrm{km\,s^{-1}}$ to $\simeq 1600$–$1700\,\mathrm{km\,s^{-1}}$ with increasing absolute values of the radial velocity. This is in contrast to the single most probably kick velocity of $\simeq 150\,\mathrm{km\,s^{-1}}$ found by Willems & Kalogera (2004). The wider

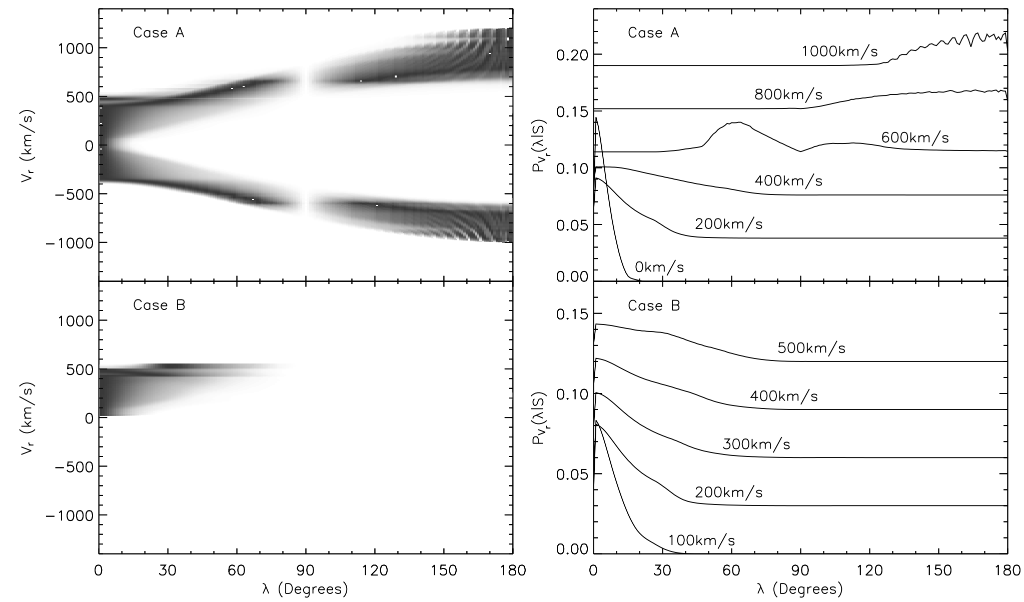

Figure 3. As Fig. 1, but for the spin-orbit misalignment angle λ.

range found here is associated with the relation between the kick magnitude and the post-SN peculiar velocity which tends to select those kick velocities from the admissible range which are able to explain the motion of the system in the Galaxy (high space velocities cannot be explained by low kick velocities and vice versa). However, for a given radial velocity, the range of kick velocities with non-vanishingly small probabilities is always much more constrained than in Willems & Kalogera (2004).

The tilt-angle distributions, on the other hand, clearly favor tilt angles below 30°–50° when (i) the system has crossed the Galactic plane twice in the past or (ii) the system has crossed the Galactic plane once and has a current radial velocity of less than $\simeq 500\,\mathrm{km\,s^{-1}}$ in absolute value. Higher tilt angles tend to be associated with one disk crossing and much higher radial velocities of $\simeq 500$–$1200\,\mathrm{km\,s^{-1}}$ in absolute value. Tilt angles close to 90° are furthermore strongly disfavored for any radial velocity V_r. The overall behavior of the PDFs thus supports the tilt angles of $16^\circ \pm 10^\circ$ or $164^\circ \pm 10^\circ$ predicted by the geometrical model of Jenet & Ransom (2004), as well as the problems with their alternative solutions of $82^\circ \pm 16^\circ$ or $98^\circ \pm 16^\circ$ which are incompatible with the misalignment angle between the pulsar's spin and magnetic dipole axes derived by Demorest et al. (2004).

4. Non-isotropic kicks

In view of recent claims of alignment of NS kicks with NS spin axes (e.g., Romani, in this volume), it is also interesting to consider the constraints on the progenitor and formation of PSR J0737−3039 in the case where the kick direction is confined within two oppositely directed cones with an opening angle of 30° and with axes parallel to the pre-SN orbital angular momentum axis (i.e., polar kicks). The confinement of the kick directions strongly reduces the range of radial velocities for which viable progenitors for PSR J0737−3039 may be found and greatly tightens the constraints described in the previous sections: the mass of pulsar B's helium star progenitor becomes constrained to $M_0 \simeq 2.1$–$2.5\,M_\odot$, the pre-SN orbital separation to $A_0 \simeq 1.1$–$1.5\,R_\odot$, and the magnitude of the kick velocity to $V_k \simeq 100$–$600\,\mathrm{km\,s^{-1}}$. The range of most probable kick velocities furthermore shrinks to $\simeq 200$–$550\,\mathrm{km\,s^{-1}}$, and the range of most probable tilt angles to 15°–45°.

5. Concluding remarks

We have used the scintillation velocity measurements of Ransom et al. (2004) to derive the most up-to-date constraints on the progenitor of PSR J0737−3039 and on the kick imparted to pulsar B at birth as a function of the unknown orientation Ω of the systemic velocity projected on plane of the sky and the unknown radial velocity V_r. We also derived the most probable pulsar kick velocity and spin tilt for both isotropic and polar kicks as a function of V_r. Once Ω is measured in the coming year, it will be straightforward to use the results presented here to further constrain the natal kicks and the spin-tilt predictions.

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