The Origin of the Binary Pulsar J0737-3039B

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Evolutionary scenarios suggest that the progenitor of the new binary pulsar J0737-3039B\textsuperscript{1,2} was a He-star with $M > 2.1 - 2.3\,M_\odot$. We show that this case implies that the binary must have a large ($> 120\,\text{km/s}$) center of mass velocity. However, the location, $\sim 50\,\text{pc}$ from the Galactic plane, suggests that the system has, at high likelihood, a significantly smaller center of mass velocity and a progenitor more massive than 2.1 $M_\odot$ is ruled out (at 97\% c.l.). A progenitor mass around 1.45 $M_\odot$, involving a new previously unseen gravitational collapse, is kinematically favored. The low mass progenitor is consistent with the recent scintillations based velocity measurement of $66\pm 15\,\text{km/s}$ \textsuperscript{3} (and which also rules out the high mass solution at 99\% c.l.) and inconsistent with the higher earlier estimates of $141\pm 8.5\,\text{km/s}$ \textsuperscript{2}. Direct proper motion measurements, that should be available within a year or so, should better help to distinguish between the two scenarios.

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The remarkable binary system J0737-3039\textsuperscript{1,2} is composed of two pulsars denoted A and B. We show here that the orbital parameters of this system and its location close to the galactic plane pose strong limits on the origin of this binary system and on the progenitor’s mass of the younger pulsar B.

The separation, $R$, (i.e., the sum of the semi-major axes) of the pulsars today is $8.8 \times 10^{16}\,\text{cm}$ and the eccentricity, $e$, is 0.087779. Both $R$, and $e$ decrease with time due to gravitational radiation emission and the system will merge in approximately 85 Myr from now. The periods $P_{A,B}$ and their time derivatives provide upper limits for the life times of the pulsars: $t_A \approx 210\,\text{Myr}$ and $t_B \approx 50\,\text{Myr}$. Integration backwards in time yields the system’s parameters at birth, 50 Myr ago when B was born: $R \approx 10^{11}\,\text{cm}$ and $e \approx 0.11$, both only slightly larger than the present values. The values 210 Myr ago were not that different: $R = 1.2 \times 10^{11}\,\text{cm}$ and $e \approx 0.14$. As these parameters did not notably evolve, our analysis is insensitive to the exact age of the pulsar.

Dewi and van den Heuvel\textsuperscript{3} and Willems and Kalogera\textsuperscript{4} considered a scenario in which the progenitor star lost most of its envelope through interaction with its companion A. Prior to the formation of the second pulsar, tidal interaction between the progenitor and the neutron star has led to a circular orbit. Since most of the lost mass could not have accreted onto the companion, it was probably lost through a common envelope phase, at which point the companion J0737-3039A was spun up and its magnetic field was suppressed by accretion. They estimate that the progenitor mass was more massive than 2.3 $M_\odot$\textsuperscript{3} or 2.1 $M_\odot$\textsuperscript{4} respectively. This limit follows from standard evolutionary scenarios, leading neither to neutron star formation nor to core collapse, from progenitors that are less massive than 2.1 – 2.3 $M_\odot$\textsuperscript{3}. The formation of the second pulsar is described according to the current picture by a core collapse event that involves a supernova and mass ejection from the system.

We consider now the influence of mass ejection during the formation of the second pulsar, on the orbital motion. The thrust of the ejected mass, $\Delta m$, gives a velocity, $v_{cm}$, to the center of mass (CM) of the remaining system. In addition, the mass loss would lead to an elliptic orbit or even to the disruption of the system. For a spherically symmetric mass loss, $v_{cm}$ will be:

$$v_{cm} = \frac{m_{Bi} \Delta m}{(m_A + m_B)^{3/2} (m_A + m_{Bi})^{1/2}} v_K$$ \textsuperscript{1}

where $v_K \equiv \sqrt{G(m_A + m_B)/R}$ is the Keplerian velocity of the two stars relative to each other, just after the explosion, with $R$ being the distance between the two stars at that time. Within the context of J0737-3039, $m_A = 1.377(5) M_\odot$, $m_B = 1.250(5) M_\odot$, $\Delta m$ is, of course, unknown and $m_{Bi} = m_B + \Delta m$ is the initial mass of B, while $v_K \approx 600\,\text{km/s}$. With $m_A \approx m_B$, $v_{cm}$ would be of the order of $v_K/2$ unless $\Delta m \ll m_B$. The birth of the system with a low eccentricity and $\Delta m \approx m_B$ requires for B to have had a natal kick\textsuperscript{4}. This kick will increase $v_{cm}$ further and the above value can be considered as a lower limit. In other words, the nearly circular orbit today implies either a large CM velocity, roughly as given by Eq.\textsuperscript{1} or a small ejected mass $\Delta m \ll m_B$.

Fig. 1 depicts change in the CM velocity (relative to the unknown CM velocity prior to the explosion) for a system with two masses moving on a circular orbit, assuming the new binary system attains the initial eccentricity of J0737-3039 (0.088 $\leq e < 0.14$). In the following we assume that this initial CM velocity was small and we approximate $v_{cm} \approx \Delta v_{cm}$. We will return to this point in the conclusions. Fig. 1 shows that the minimal CM velocity for a 2.1 $M_\odot$ progenitor is 120 km/s.

Recently Ransom et al.\textsuperscript{6} have estimated $v_{cm,1}$, the CM velocity of the binary on the plane of the sky, using the observed scintillations of the system. They find a rather large value: $v_{cm,1} = 141 \pm 8.5\,\text{km/s}$ (with 96.0 $\pm 3.7$...
km/s along the orbit and 103.1 ± 7.7 km/s perpendicular to it). This value excludes the region in Fig. 1 left of a vertical line of ~141 km/s. However, these findings were questioned recently by Cole et al. who suggested that the scintillation pattern is anisotropic. When including anisotropy, they find a much lower value: \(v_{\text{cm}} \approx 66 ± 15\) km/s. The region in Fig. 1 to the right of the vertical line of ~66 km/s is consistent with this observation.

However, the system can be additionally constrained. The observed distance of the system from the Galactic plane, \(z_{\text{obs}} \approx 50\) pc, enables us to place a statistical upper limit on \(v_{\text{cm}}\). Stars move in a periodic motion in the vertical direction. For small vertical oscillations, the potential of the Galaxy is harmonic: \(\Phi = 2\pi G \rho_0 z^2\), where \(\rho_0 \approx 0.25\) M\(_\odot\)/pc\(^3\) is the mass density in the disk. This gives a vertical orbital period, \(P_z \approx 50\) Myr. The typical velocity for an object at \(z_{\text{obs}}\) is \(v_z \approx 2\pi z_{\text{obs}}/P_z\). \(z_{\text{obs}} \approx 50\) pc implies then that the expectation value of the vertical velocity is of the order of 6 km/s.

To quantify the probability for having a particular CM velocity given the observed \(z_{\text{obs}}\), we perform Monte Carlo simulations that follow the formation of the system. We assume that star B had a given mass \(m_{B1}\), and that a randomly oriented kick \(v_{\text{kick}}\) was given to it. We also assume that the progenitor distribution has an initial Gaussian distribution in the amplitude of the vertical oscillation, with a width \(\sigma_z = 50\) pc (other \(\sigma_z\) <100 pc gave very similar results). At the moment of formation, we assume it had a random phase within its vertical motion. We calculate the CM kick velocity \(v_{\text{cm}}\), and assign it a random direction, then integrate the vertical motion of the pulsar for 50 Myr using a realistic galactic potential.

Fig. 2a depicts the probability that a system with a given \(m_{B1}\) and \(v_{\text{kick}}\) could find itself with \(0.087 < e < 0.14\) after 50 Myr, within 50 pc of the galactic plane and with a transverse velocity of 66 ± 15 km/s as measured by Coles et al. For comparison, Fig. 2b depicts similar simulations but without the assumption on the transverse velocity. Here the initial conditions are less constrained. Fig. 4c repeats the first panel, with the modified condition that the \(e < 0.14\) instead of 0.087 < \(e < 0.14\). One can see that qualitatively the results do not change. Fig 4d is a repeat of the first panel with the transverse velocity assumed to be 141±8.5 km/s, as measured by Ransom et al., with the scintillation anisotropy neglected.
Without the additional information on the CM velocity, we find that that even if $v_{kick}$ is fine tuned to be near either 130 or 315 km/s, a system with a mass of $m_{Bi} = 2.1 M_\odot$ could result with the observed configuration in only about 3% of the random realizations (as compared with the most favorable conditions having lower $m_{Bi}$ and $v_{kick}$). Other $v_{kick}$'s, or higher mass systems are kinematically even less likely. On the other hand, low ejected mass solutions are favored. If we add the constraint that the transverse velocity is $66 \pm 15$ km/s, then a fine tuned $m_{Bi} = 2.1 M_\odot$ model can be ruled out at even 99% c.l. The results, are though, qualitatively different if we take the CM velocity on the plane of the sky as $141$ km/s. Much larger kicks, of a few hundred km/s are essential now. While the “cannonical” $2.1 M_\odot$ or higher solution is not really favorable yet, the previously most favorable low mass ($1.4 M_\odot$) progenitor is ruled out. Instead an “intermediate” mass of $\sim 1.7 M_\odot$ is the most likely one.

If we assume that the transverse measurement of Coles et al. [5], which allows for the scintillation to be anisotropic, then at better than 99% confidence, the progenitor of star B was less massive than $2.1 M_\odot$. This is just the lower limit of Willems and Kalogera [2] and it is slightly below the lower limit of Dewi and van den Heuvel [3] for the progenitor mass in a standard core collapse scenario. An inspection of Fig. 2a reveals that there is a kinematically favorable solution with a small mass loss and natal kicks ranging from 0 to $\sim 100$ km/s. Since a small mass loss necessarily implies a small natal kick, the solutions with $v_{kick} \geq 100$ km/s are physically unlikely. If we therefore limit ourselves to $v_{kick} \leq 30$ km/s, then without fine tuning, a large fraction of the progenitor systems will result with the observed configuration with a progenitor mass of $1.45 M_\odot \leq m_{Bi} \leq 1.65 M_\odot$. Thus, a mass loss of about $0.3 \pm 0.1 M_\odot$ is most probable. The results are qualitatively the same even if we do not enforce that the resulting system has a CM velocity of 66 km/s, or if we replace the condition on the eccentricity to $e < 0.14$ rather than $0.088 < e < 0.14$.

At a distance of 600 pc a velocity on the plane of the sky, $v_{cm,\perp}$, implies a proper motion of $0.036(v_{cm,\perp}/100$ km/s) $''$/yr. This should be compared with the current errors of $\sim 0.04''$ in the position of the system. This comparison suggests that within a year or so we could obtain a direct limit on the peculiar motion. A comparison of this peculiar motion with the motion measured using scintillations would confirm the anisotropy estimates that arise from the scintillations measurements. The break down to the different components should allow us to measure the orientation of the orbital plane in the sky. Thus within a year or two we should be able to nail down the two components of the CM motion on the plane of the sky as well as the orientation of the orbital plane! The knowledge of the vertical component (relative to the galactic plane) would tell us whether the position of the system in the galactic plane is natural (if the vertical component is small) or an unlikely coincidence (if this velocity is large).

We are left with two physically distinguished scenarios for the formation of pulsar B. In the first, the progenitor is a kinematically “unlikely” but theoretically plausible $2.1 - 2.3 M_\odot$ He-star progenitor—around the minimal masses estimated from stellar evolution scenario [3, 4]. In the second scenario, the progenitor is a kinematically favorable $\sim 1.5 M_\odot$ young stellar core. The more probable low mass solution requires a new type of stellar collapse. Intermediate solutions are neither statistically favored nor do they fit any plausible theoretical scenario.

Before turning to the implications of these two solutions we consider, first, three assumptions made in our analysis. (i) We have assumed that prior to the formation of the second pulsar the system was in a circular motion. This follows from all evolutionary scenarios that lead to a neutron star and a small mass progenitor (even a $2.3 M_\odot$ is a very small mass progenitor). (ii) We have assumed that the second mass loss was instantaneous, namely, shorter than a fraction of an orbital period. Given that the orbital motion is of several hundred km/s while typical mass ejection velocities in SNe are higher than 10,000 km/s, this assumption is reasonable (for all conventional neutron star formation scenarios). (iii) We have assumed that the CM velocity, prior to the formation of the second pulsar was small. One would expect that the system would have acquired a CM velocity during the formation of the first pulsar. About half of the system’s mass was lost during this event and this should have resulted in some CM velocity. However, this velocity would have been of the order of half the Keplerian velocity of the system at that time (see Eq. 11). Given the fact that the orbital separation was much larger we could reasonably expect, but not prove, that this velocity was of order of several tens of km/s. Moreover, if the system would have acquired a large CM velocity in the first SN, there would have been an even smaller probability to find it in the galactic plane today.

We turn now to the most likely scenario, the very low mass scenario. We imagine the same evolutionary scenario in which some time before 50 Myr, system A and progenitor B were in a common envelope phase and B lost most of its mass keeping practically just its core of $\sim 1.45 M_\odot$. This progenitor leads to a small CM motion and does not require any kick velocity. This solution is kinematically preferred. However, it requires a new mechanism for the formation of the pulsar as He-stars of $1.45 M_\odot$ do not collapse to form neutron stars [6, 7]. The observation that the progenitor mass is very close to the Chandrasekhar mass leads us to conjecture that the process involves the collapse of a supercritical white dwarf. For example, the progenitor may have been a degenerate bare core just above the critical Chandrasekhar mass, supported by the extra thermal pressure against collapse. As it cooled, the additional support was lost and the core collapsed to form a neutron star. A second possibility is that it was formed just below the Chandrasekhar mass, and as it cooled, neutronization at the
core increased the baryon to electron ratio, and with it reduced the Chandrasekhar mass until the progenitor became unstable and collapsed. Note that the object must have been composed of O-Ne-Mg as a collapsing CO core would have carbon-detonated and it would have exploded completely forming a type I SNe and leaving no remnant. This solution clearly requires a new type of formation scenario for neutron stars.

This new solution passes an immediate non trivial test. With a small mass loss, only small kick velocities are possible and in fact we can estimate in this case (see Fig. 2) the mass loss needed to obtain the initial eccentricity \( e \approx 0.11 \). We find (while conservatively assuming that the collapse took place \( 50^{+100}_{-50} \) Myr ago) \( \Delta m = e(1 + q) m_B = 0.28 \pm 0.07 \) M\(_{\odot}\) and a progenitor mass of \( 1.53 \pm 0.07 \) M\(_{\odot}\), which is, indeed, just above the Chandrasekhar limit. Intriguingly, some mass loss, in the form of \( \nu \) losses of a few times \( 10^{53} \) ergs, must take place. The estimated \( \Delta m \) corresponds to \( E_\nu \approx \Delta m e^2 \approx 4.2 \times 10^{53} \) ergs, which is in the right range. Of course, if some mass is ejected as well, \( E_\nu \) will be smaller and a small kick could arise, but the total mass-energy lost will be the same. The consistency of this mass and energy loss with the previous physical picture increases our belief in this new and unusual scenario.

The other, higher mass scenario of \( 2.1 - 2.3 M_\odot \) (which is still on the lowest end of the evolutions scenarios) is the most likely from a stellar evolution point of view. However, as we have seen it is quite unlikely statistically. Specifically, it implies a post-kick CM velocity of at least 125 to 150 km/s, which was within a few degrees from the Galactic plane for it to find itself in the plane today. To be consistent with the low \( v_{cm,\perp} \), it should also be pointing within about 25\(^\circ\) from us, or in the opposite direction. In other words, it should have a minimum velocity of at least 100 km/s in the direction of the line of sight, if progenitor B was a 2.1M\(_{\odot}\) star. More massive progenitors imply even larger velocities. Of course it cannot be ruled out. We might be observing a very improbable system. However, if this is the case, the “unlikeliness” of the system should be taken into consideration when performing population synthesis and estimating neutron star mergers rate based on this observation. Specifically, with a very large CM velocity, as such a system must have, it is very unlikely to find it in the Galactic plane. Most such systems should exist high above the Galactic disk. Anticipating this, Narayan, Piran & Shemi [14] considered this effect by taking an effective scale height of 5kpc for the Galactic binary NS systems. This value was used later by others. It may be that even this high value is too low. This in turn might boost up the estimated rates of NS merger by a significant factor.

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