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J0453+1559: A Neutron Star–White Dwarf Binary from a Thermonuclear Electron-capture Supernova?

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Abstract

The compact binary radio pulsar system J0453+1559 consists of a recycled pulsar as primary component of $1.559(5)\,M_\odot$ and an unseen companion star of $1.174(4)\,M_\odot$. Because of the relatively large orbital eccentricity of $e = 0.1125$, it was argued that the companion is a neutron star (NS), making it the NS with the lowest accurately determined mass to date. However, a direct observational determination of the nature of the companion is currently not feasible. Moreover, state-of-the-art stellar evolution and supernova modeling are contradictory concerning the possibility of producing such a low-mass NS remnant. Here we challenge the NS interpretation by reasoning that the lower-mass component could instead be a white dwarf born in a thermonuclear electron-capture supernova (tECSN) event, in which oxygen–neon deflagration in the degenerate stellar core of an ultra-stripped progenitor ejects several $0.1\,M_\odot$ of matter and leaves a bound ONeFe white dwarf as the second-formed compact remnant. We determine the ejecta mass and remnant kick needed in this scenario to explain the properties of PSR J0453+1559 by a NS–white dwarf system. More work on tECSNe is needed to assess the viability of this scenario.

Unified Astronomy Thesaurus concepts: Late stellar evolution (911); Neutron stars (1108); White dwarf stars (1799); Compact binary stars (283); Supernovae (1668); Binary pulsars (153); Supernova remnants (1667)

1. Introduction

The precise measurements of neutron star (NS) masses play a crucial role in modern astrophysics for many reasons. Their upper limit, currently about $2.0\,M_\odot$ (Antoniadis et al. 2013; Cromartie et al. 2019), can be used to constrain the equation-of-state (EoS) of high-density nuclear matter (Lattimer 2016; Özel & Freire 2016), as well as for improving our understanding of the final stages of massive star evolution (Langer 2012) and the subsequent supernova (SN) explosion (Janka 2012; Sukhbold et al. 2016). The lower limit of NS masses, however, has received much less attention in the literature until recently, although it has similarly important consequences for improving our knowledge, in particular on SNe and stellar evolution near the lower-mass end of exploding stars (e.g., Müller et al. 2019) and on the nuclear EoS of NSs, if the baryonic core mass of its progenitor were known (e.g., Klähn et al. 2006).

The binary radio pulsar J0453+1559 was discovered by Martinez et al. (2015). It is a mildly recycled 45 ms pulsar in a 4.07 days orbit with an unseen companion star. The mass of the $1.559(5)M_\odot$ pulsar and its $1.174(4)M_\odot$ companion star were measured to high accuracy from detections of post-Keplerian parameters: the rate of advance of periastron and the Shapiro delay. The measured spin period derivative of $\dot{P} = 1.86 \times 10^{-19}$ and the estimated surface magnetic field of about 3×10^9 G strongly suggest that this pulsar was mildly recycled by the accretion of matter from the progenitor of the companion star (e.g., Tauris & van den Heuvel 2006).

The double NS nature of this binary was concluded from the measured orbital eccentricity of the system ($e = 0.1125$), which is an expected relic of a second SN in the system. As seen in Figure 1, the eccentricity of PSR J0453+1559 is indeed typical among the known population of double NS systems in the Galactic disk. On the contrary, the eccentricities of recycled pulsars with massive white dwarf (CO or ONeMg WD) companions are much smaller, at least by a factor of 100. The reason for this is that the circularization process of binaries, arising from the strong tidal torques during mass transfer, will leave behind almost perfectly circular systems with very small eccentricities. In systems where this mass-transfer epoch is followed by a SN explosion, the eccentricity instantaneously increases to values typically between 0.1 and 1, due to the sudden mass loss and a potential kick added to the newborn NS (Hills 1983). It is therefore clear that *if* PSR J0453+1559 is not a double NS system, then special circumstances are needed to produce the observed eccentricity. We notice that there are several known WDs in binaries that have masses $> 1.1\,M_\odot$ (e.g., Mereghetti et al. 2011; Bates et al. 2015). No optical companion has been found at the position of PSR J0453+1559 (Martinez et al. 2015). However, a detection is not expected even if the system hosts a massive WD, given the distance (1.1 kpc) and rapid cooling of such a massive WD.

Explaining the origin of a $1.17\,M_\odot$ NS from stellar core-collapse SNe is not straightforward, and it is evident that stellar evolution modeling for $M_{\rm ZAMS} \leqslant 11\,M_\odot$ remains a challenging task (Woosley & Heger 2015). Super-AGB stars are the lowest-mass progenitors whose degenerate cores can become unstable to gravitational collapse. Their ONeMg cores, however, have a mass of $\sim$1.35–1.36 $M_\odot$ (Zha et al. 2019) and collapse to NSs of similar baryonic mass (Kitaura et al. 2006; Janka et al. 2008; Fischer et al. 2010; Hüdepohl et al. 2010), corresponding to gravitational masses between $\sim 1.22\,M_\odot$ and $\sim 1.24\,M_\odot$ (via Equation (36) of Lattimer & Prakash 2001, for NS radii of 11–12 km). Although some investigations of stars with zero-age main-sequence (ZAMS) masses of $9.35\,M_\odot \leqslant M_{\rm ZAMS} \leqslant 9.75\,M_\odot$, which possess low-mass CO-cores and Fe-cores of less than $1.3\,M_\odot$ (Suwa et al. 2018), as well as studies of stars in the mass range $M_{\rm ZAMS} < 12\,M_\odot$ (Müller et al. 2016), have determined possible progenitors of $M_{\rm NS} < 1.2\,M_\odot$ NSs, the large population of such low-mass NSs predicted by the

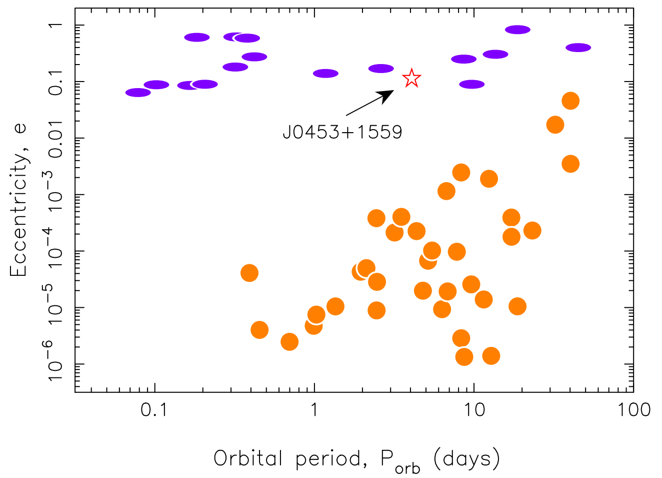

Figure 1. Eccentricity vs. orbital period for Galactic disk pulsars with NS companions (purple ellipses) and for recycled pulsars with massive (CO or ONeMg) WD companions (orange circles). The position of PSR J0453+1559 is marked with a red star. Data from ATNF Pulsar Catalogue in 2019 September (Manchester et al. 2005).

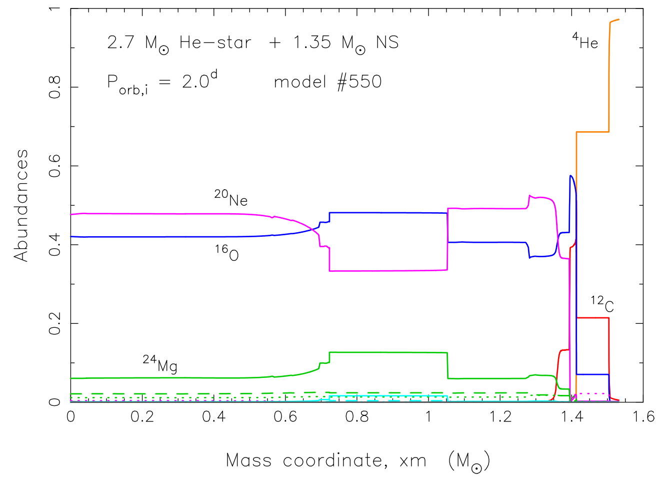

Figure 2. Final chemical abundance structure of an evolved 2.7 $M_\odot$ helium star prior to a potential tECSN event. Here a calculation is shown for a case with an accreting NS of 1.35 $M_\odot$ in an initial orbit of 2.0 days (Tauris et al. 2015). After mass transfer, the final mass of the exploding star is 1.53 $M_\odot$, with a metal core of 1.42 $M_\odot$. The total amount of Mg is 0.159 $M_\odot$, of which 0.109 $M_\odot$ is ^{24}Mg.

parameterized explosion models of Müller et al. (2016) seems incompatible with observations (Antoniadis et al. 2016) and may point to a problem. Furthermore, SN explosion simulations based on other state-of-the-art sets of progenitors do not support the possibility of NS formation with masses below $\sim$1.20 $M_\odot$; see Sukhbold et al. (2016) and Burrows et al. (2019) for single stars and Ertl et al. (2019) and Müller et al. (2019) for progenitors in binaries.

Therefore, it is a viable question whether the pulsar companion of J0453+1559 could possibly be a WD instead of n NS. Here in this Letter, we propose that the recently advocated existence of so-called thermonuclear electron-capture SNe (tECSNe), i.e., incomplete explosions of degenerate ONeMg cores by oxygen deflagration leaving behind bound ONeFe WD remnants (Jones et al. 2016, 2019; Kirsebom et al. 2019), might offer a formation scenario of J0453+1559 as a NS–WD binary. This model has the advantage that it does not invoke the difficult production of a NS of only 1.17 $M_\odot$. At the same time, it can explain the observed eccentricity, arising from explosive mass loss of a few 0.1 $M_\odot$.

2. Results

For a symmetric SN, the relation between the post-SN orbital period ($P_{\rm orb}$) and the pre-SN orbital period ($P_{\rm orb,0}$) is simply given by (Bhattacharya & van den Heuvel 1991): $P_{\rm orb} = P_{\rm orb,0}\ \mu/(2\mu - 1)^{3/2}$, where $\mu = (M_{\rm rem} + M_{\rm comp})/(M_{\rm He} + M_{\rm comp})$ is the ratio between the total system mass after and before the SN. The post-SN eccentricity is given by $e = (1 - \mu)/\mu$. Here the pre-SN mass of the exploding star is denoted by $M_{\rm He}$; its (gravitational) remnant mass is denoted by $M_{\rm rem}$, and $M_{\rm comp}$ is the mass of the companion star. In the case of PSR J0453+1559, we have $M_{\rm comp} = 1.559\, M_\odot$ and $M_{\rm rem} = 1.174\, M_\odot$ (Martinez et al. 2015). Thus, for a symmetric SN (i.e., without any kick, $w = 0$), we find $M_{\rm He} = 1.481\, M_\odot$ in order to achieve $e = 0.1125$.

Assuming that the threshold mass for undergoing a tECSN is $\sim$1.39 $M_\odot$ (Jones et al. 2016), we would need a progenitor star with a $\sim$1.39 $M_\odot$ metal core and an envelope of $\sim$0.09 $M_\odot$ for this scenario to work for a symmetric SN. Indeed, such (ultra-stripped) SN progenitor models in close binaries where the first-formed compact object is a NS were studied in detail by Tauris et al. (2015). In their Table 1, we find such ultra-stripped progenitors for binary models calculated from initial helium star masses of 2.6 and 2.7 $M_\odot$, and an initial orbital period of 2.0 days. Furthermore, these two models have final core masses of 1.37 and 1.42 $M_\odot$ and final total stellar masses of 1.46 and 1.53 $M_\odot$, respectively—see Figure 2. For a symmetric SN producing PSR J0453+1559, the pre-SN orbital period must be $P_{\rm orb,0} = 3.23$ days (given that the present[4] observed orbital period of the system is $P_{\rm orb} = 4.07$ days), whereas the models quoted above were computed with initial orbital periods of 2.0 days, yielding somewhat smaller $P_{\rm orb,0} = 1.6$–1.8 days. However, rerunning one of the Tauris et al. models with adjusting the companion mass to 1.559 $M_\odot$ and the initial orbital period to 3.0 days (keeping all input physics of the code unchanged) yields a pre-SN orbital period of 3.17 days and an exploding star of total mass 1.59 $M_\odot$. Thus, further below, we consider the kinematic effects by mimicking tECSNe of stars with total masses between 1.46 and 1.59 $M_\odot$ (and ONeMg cores of $\lesssim$1.4 $M_\odot$).

The effect of a symmetric tECSN producing PSR J0453+1559 results in a 3D systemic recoil velocity of about 12 km s^{-1}. However, proper motion observations of the system (Martinez et al. 2015) point to a likely 3D systemic velocity of order 36–85 km s^{-1} (corrected for Galactic rotation and location of the binary; Tauris et al. 2017), depending on the exact distance to the source and unknown projection of the velocity vector into the plane of the sky. The remaining contribution to the systemic velocity could come either from the first SN of the system, or as a result of a kick during the tECSN.

With respect to the former possibility, simulations (M. Kruckow 2019, private communication; see also Kruckow et al. 2018) show that an additional contribution to the systemic velocity of $\sim$25 km s^{-1} is not uncommon. In particular, given

[4] The decay of the orbit due to gravitational-wave damping since the formation of the PSR J0453+1559 system is negligible given its relatively large orbital period.

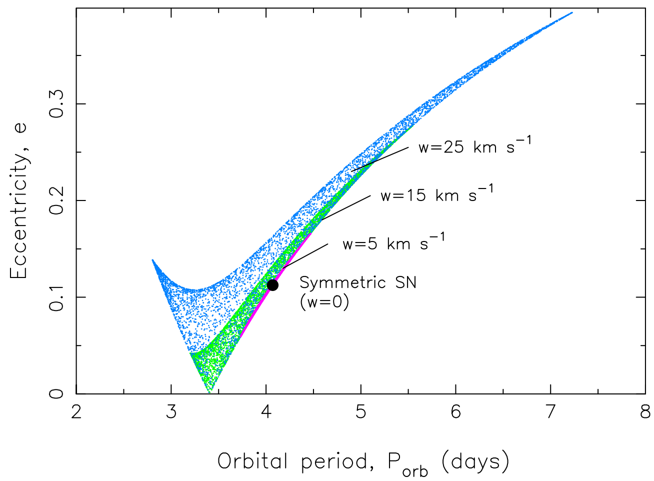

Figure 3. Simulation of post-SN systems in the orbital period–eccentricity plane, based on the properties of PSR J0453+1559 and an ultra-stripped progenitor star for the tECSN scenario (see the text). The result of a symmetric SN corresponds here to the presently observed properties of PSR J0453+1559. Four kick velocity magnitudes (color coded: $w = 0$, 5.0, 15.0, and 25.0 km s^{-1}) were each applied in 4000 SNe with random (isotropic) kick directions to illustrate the kinematic effect of even a small kick magnitude.

the large mass of the recycled NS (1.559 $M_\odot$) in this system, it is likely that the first SN produced a fairly large NS kick at birth (Janka 2017; Tauris et al. 2017), resulting in a significant systemic velocity, in agreement with observations of the proper motion.

For the latter possibility, a kick of at least 69 km s^{-1} is required to obtain a minimum systemic recoil velocity of 36 km s^{-1} (see below for details), but only if the estimated systemic velocity would originate exclusively from a kick. More work on tECSN is needed to quantify such possible kicks. A dipole asymmetry a_d of the radial ejecta momentum, i.e., $p_{\mathrm{ej},r}(\theta) = p_{\mathrm{ej},0}(1 + a_\mathrm{d}\cos\theta)$, leads to a kick of the compact remnant of the explosion (a WD for the tECSN case, but similarly for a NS in the case of a core-collapse SN) of $w = \alpha_\mathrm{ej} M_\mathrm{ej} M_\mathrm{rem}^{-1} v_\mathrm{ej}$, where $M_\mathrm{ej} v_\mathrm{ej}$ is the radial ejecta momentum for ejecta mass M_ej with average velocity v_ej, and

$$\alpha_\mathrm{ej} = \frac{\int_{-1}^{+1} \mathrm{d}\cos\theta\ (1 + a_\mathrm{d}\cos\theta)\cos\theta}{\int_{-1}^{+1} \mathrm{d}\cos\theta\ (1 + a_\mathrm{d}\cos\theta)} = \frac{1}{3}\,a_\mathrm{d} \tag{1}$$

is the relevant ejecta asymmetry parameter. In order to obtain a kick of ~70 km s^{-1}, for a WD of 1.17 $M_\odot$ and an ejecta mass of ~0.3 $M_\odot$ expelled with an average speed of 10^4 km s^{-1}, one needs an ejecta asymmetry α_ej of about 2.7%, corresponding to a dipole moment of the ejecta momentum of $a_\mathrm{d} = 0.08$. In view of the considerable ejecta asymmetry produced in the oxygen deflagration simulations of Jones et al. (2016, 2019), such a magnitude of the dipole component of the radial momentum distribution appears to be well within reach.

Inferring the precise progenitor system values of PSR J0453+1559 given the current post-SN data is difficult, even in cases where only a small kick was at work during the formation of the second-born compact object (being a NS or an ONeFe WD). We illustrate in Figure 3 the effects of a small kick applied to the second-formed compact object in PSR J0453+1559. This model takes its basis in a 1.48 $M_\odot$ exploding star, leaving behind a remnant with a mass of 1.174 $M_\odot$. The pre-SN orbital period is 3.23 days and the mass of the companion star (the recycled NS) is 1.559 $M_\odot$. With these input values, a symmetric SN will leave behind a system with orbital parameters similar to PSR J0453+1559, whereas a small kick of 25 km s^{-1} is seen to produce systems with $0 < e < 0.4$, depending on the kick direction. Applying larger kicks would lead to a wider range of post-SN eccentricities and possibly disruption of the system.

As pointed out above, indeed a larger kick is needed *if* the systemic velocity of PSR J0453+1559 ($\gtrsim$36 km s^{-1}) will be explained exclusively by the second SN (both in the case of a tECSN as well as a core-collapse SN). This is demonstrated in Figure 4, where we have simulated the kinematic effects of 100 million explosions mimicking tECSNe. We sampled the outcome by choosing tECSN explosions of stars of 1.46–1.59 $M_\odot$ and applying kicks between 0 and 100 km s^{-1}, whereas the companion star mass was fixed at 1.559 $M_\odot$, equal to the mass of the recycled pulsar in the J0453+1559 system. In this case, we find solutions only for $w > 69$ km s^{-1}. Here a solution refers to a system that has a similar orbital period and eccentricity as PSR J0453+1559 within an error margin of 3% and a systemic velocity compatible with the observational constraints for that binary system.

3. Discussion and Conclusions

The possibility of tECSNe instead of gravitational-collapse ECSNe with NS formation is controversial (Suzuki et al. 2019; Zha et al. 2019). It depends on the central density of the degenerate ONeMg core at oxygen ignition, which again depends on the core growth rate, convection and semiconvection, and the relevant microphysics such as electron-capture rates and Coulomb effects (Kirsebom et al. 2019; Suzuki et al. 2019; Zha et al. 2019). Moreover, it is unclear whether the bound ONeFe remnant can have a mass of 1.17 $M_\odot$ after a few 0.1 $M_\odot$ have been explosively ejected. Although cases with bound remnants of 1.2–1.3 $M_\odot$ and ejecta masses of ~0.2 $M_\odot$ and ~0.1 $M_\odot$, respectively, are presented by Jones et al. (2016, 2019), their better resolved 3D simulations suggest bound-remnant masses around 0.25–0.4 $M_\odot$ and ejecta masses around 1–1.15 $M_\odot$ (see also Kirsebom et al. 2019). However, the modeling of the latest evolution stages and of the final fate of ~8–10 $M_\odot$ stars with strongly degenerate ONeMg cores remains highly uncertain, because it depends sensitively on disputed input physics: minimum electron fraction, relative chemical mix of O/Ne/Mg, the uncertain mass-accretion rate of the degenerate ONeMg core, and on the ignition density, initial O-flame structure, and treatment of the oxygen deflagration. In view of these substantial uncertainties, our hypothetical formation scenario of a NS–WD binary with a 1.17 $M_\odot$ WD and orbital eccentricity of $e \sim 0.11$ still appears as an interesting, though speculative, possibility for J0453+1559.

We emphasize that we have previously demonstrated (Tauris et al. 2017) that all kinematic properties, as well as the spin and B-field, of the observed recycled pulsar can be well accounted for by a low-mass core-collapse SN producing a double NS system, *assuming* the possibility that a 1.17 $M_\odot$ NS can be produced in a stellar core collapse. However, here we have argued that this assumption is by no means assured, and therefore we present an alternative formation hypothesis based on the tECSN scenario

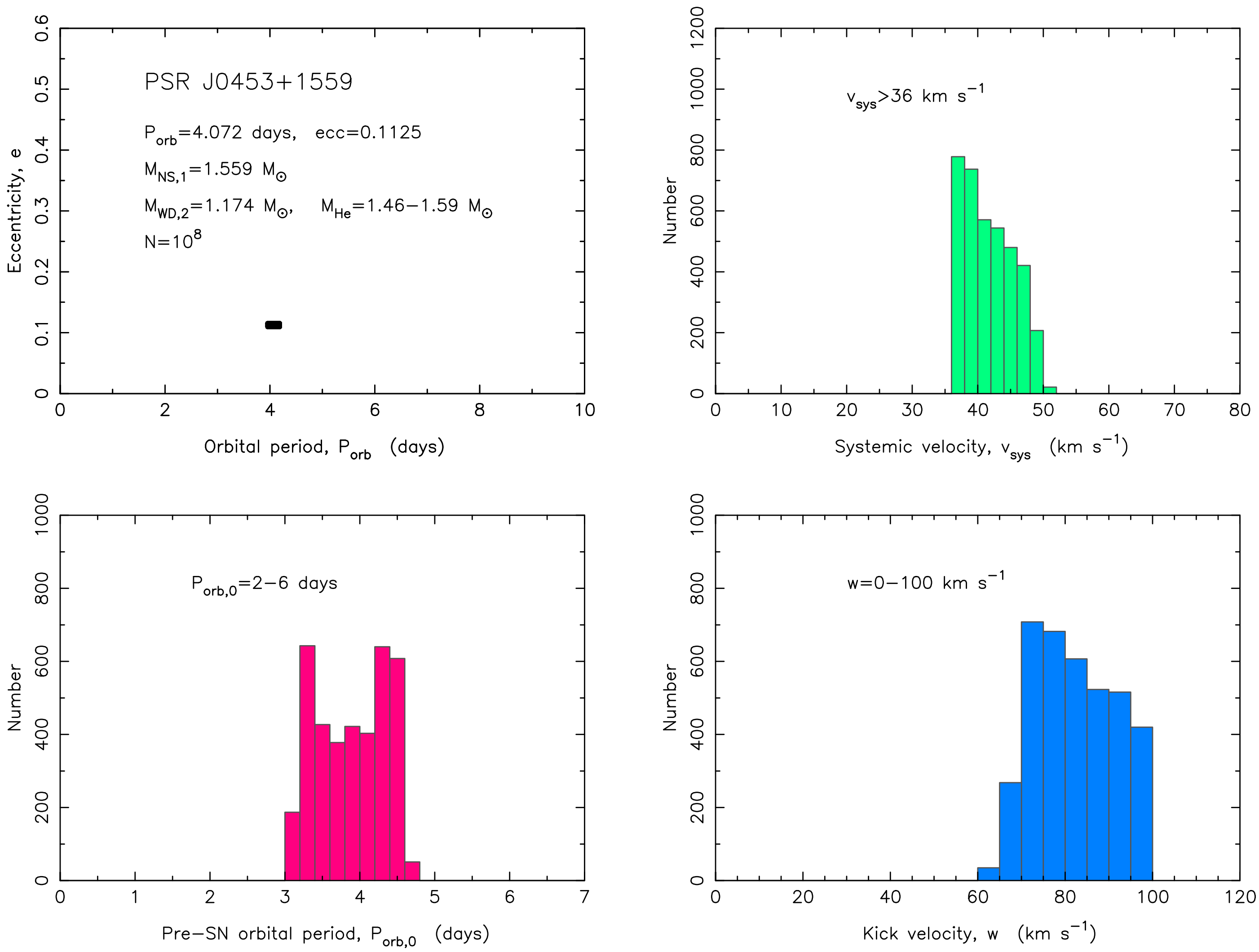

Figure 4. Formation of the PSR J0453+1559 system if composed of a NS and an ONeFe WD, based on Monte Carlo simulations of the kinematics of 100 million tECSNe, following the method of Tauris et al. (2017). The four panels display distributions of (upper left to lower right): post-SN orbital period and eccentricity, post-SN 3D systemic velocity, pre-SN orbital period, and magnitude of the kick. The total masses of the tECSN progenitor stars at the onset of explosion were chosen from a flat distribution between 1.46 and 1.59 $M_\odot$, and applied kick velocity magnitudes were chosen from a flat distribution between 0 and 100 km s^{-1}. The resulting systemic velocities from these computations are in accordance with observational data of PSR J0453+1559 if the systemic velocity originates exclusively from a kick imparted on the ONeFe WD in an asymmetric tECSN explosion (see the text).

More work on tECSNe and their stellar progenitors is needed to assess the viability of this scenario. As long as the open problems of the tECSN phenomenon as a channel of WD formation are not settled, arguments that classify PSR J0453+1559 as a double NS system on grounds of its large orbital eccentricity alone cannot be considered as rock solid.

An additional open question is whether or not other cases of compact binaries classified as double NS systems could possibly have formed via the investigated tECSN scenario, too. PSR J0453+1559 has a companion mass of 1.174(4) $M_\odot$, which is significantly lower than that of the candidate Galactic double NS system with the second lowest mass, PSR J1756−2251 with 1.230(7) $M_\odot$ (Ferdman et al. 2014). The latter could potentially be produced via an iron-core-collapse SN or a "normal" ECSN of a collapsing progenitor. The possible coexistence and differences between normal ECSNe and tECSNe also requires further investigation. Upcoming measurements of NS masses from anticipated new discoveries of binary radio pulsars by the Square Kilometre Array (SKA; Keane et al. 2015) and detection of additional double NS mergers with LIGO (Abbott et al. 2017) will constrain the minimum NS mass further and shed light on the formation paths of binary NSs as well as the final stages of stellar evolution and SN physics.

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