中國科學院新疆天文台
XINJIANG ASTRONOMICAL OBSERVATORY, CAS

ON THE FORMATION OF PSR J1640+2224: A NEUTRON STAR BORN MASSIVE?

Deng, Z.-L., Gao, Z.-F., Li, X.-D., & Shao, Y. 2020, ApJ, 892, 4

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Backgrounds

$$\frac{\dot{a}}{a} = 2\frac{\dot{J}_{orb}}{J_{orb}} - 2\frac{\dot{M}_1}{M_1} - 2\frac{\dot{M}_2}{M_2} + \frac{\dot{M}}{M}$$

- **PSR J1640+2224 consist of a millisecond pulsar and a white dwarf**
- **Parameters:**
  - Orbit period : 175 days
  - Orbital eccentricity : 7.97×10^{-4}
  - Distance : 1.51 kpc
  - Pulsar Spin period : 3.16 ms
  - Period derivative : 2.83×10^{-21}
  - Pulsar mass : ?
  - White dwarf mass : > $0.4\ M_{\odot}$ (> 90% confidence) Vigeland et al. (2018)

Model DA: $0.71^{+0.21}_{-0.20} M_{\odot}$

Model DA: $0.66^{+0.21}_{-0.19} M_{\odot}$

Backgrounds

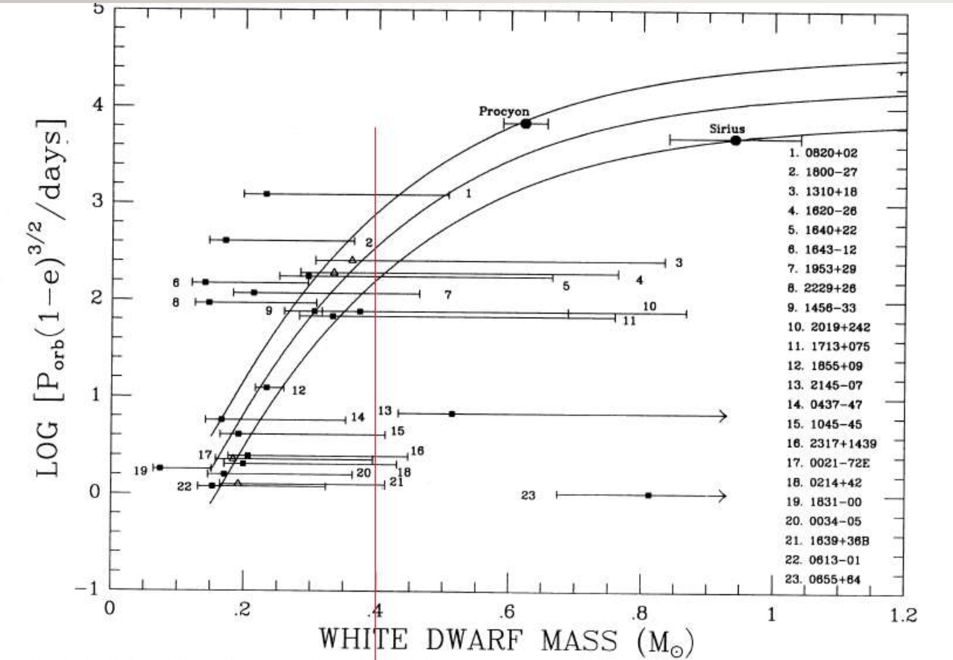
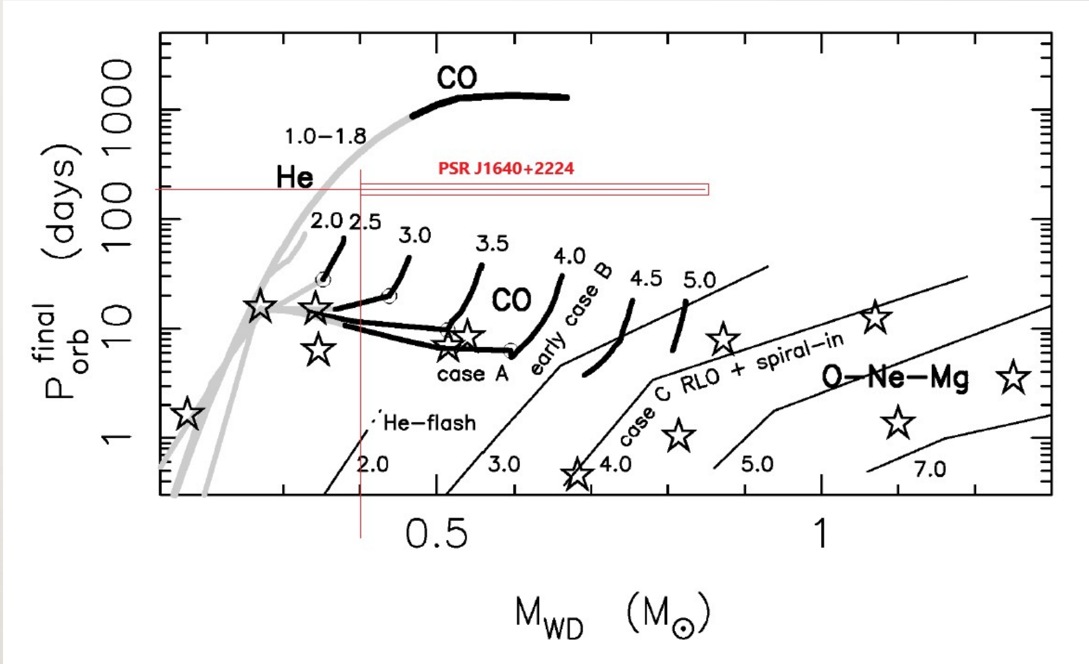
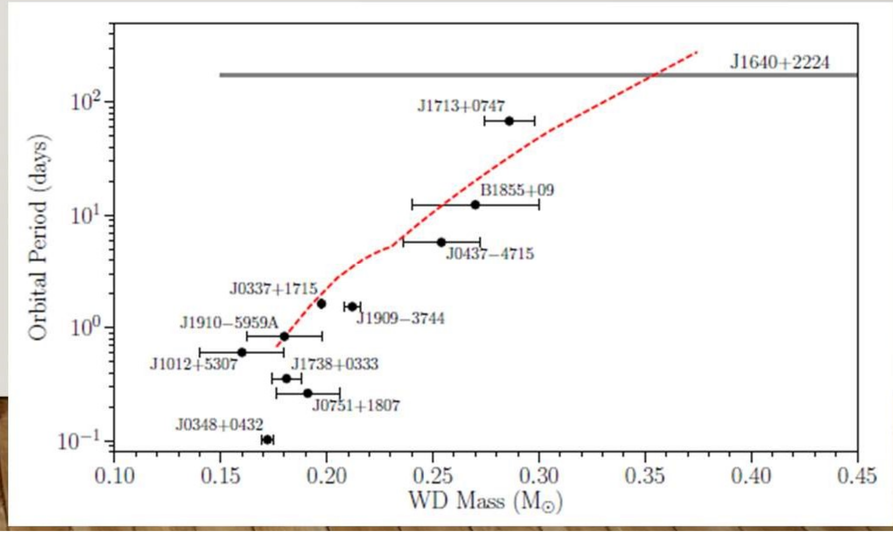


Figure 3. Orbital period–white dwarf mass relation $[P_{orb}-M_{wd}]$ for binary radio pulsars with nearly circular orbits and orbital periods longer than 1 d. The positions of 23 pulsars are taken from Table 1. Filled squares and open triangles represent pulsars in the Galactic disc and in globular clusters, respectively. For each system, the data point, left-hand error bar and right-hand error bar correspond to the median white dwarf mass, the minimum mass and the 90 per cent confidence upper limit on the mass, respectively. The solid curve is a fitting formula to the theoretical $P_{orb}-M_{wd}$ relation, given by equation (6), in the text with $R_0 = 4950\ R_\odot$. The accompanying upper and lower curves, which are factors of 2.5 from the middle curve, represent upper and lower limits on the theoretical relation. Also shown on the figure are the positions occupied by the white dwarfs in the classical binaries Sirius and Procyon, for which the same theoretical relation may apply. Note that the factor $(1-e)^{3/2}$ in the ordinate axis label is nearly unity for all except the two classical binary systems. See the text for further information on the elements of this figure.

Rappaport et al. 1995



Tauris et al. 2000



Vigeland et al. 2018

Input physics:

- Code: Modules for Experiments in Stellar Astrophysics (MESA, Paxton et al. 2013, 2015,2018)
- Model: ZAMS+NS
  - NSs initial mass: 1.4-2.2 $M_\odot$
  - Donor star initial mass: 1.0-4.0 $M_\odot$
  - Initial orbital period: 1-60 days
- Metal abundance: Pop. I (X=0.70; Z=0.02) and Pop. II (X=0.75; Z=0.001)
- Mixing-length parameter: $\alpha = \frac{l}{H_P} = 2.0$,
- Exponential diffusive overshooting with the parameter fov = 0.01-0.016 (Herwig 2000)
- Binary interactions in the mass transfer progress:
  - Gravitational radiation (GR)
  - Magnetic braking (MB)
  - Mass loss (ML)

Result (The final $P_{orb} - M_{WD}$ Diagram)

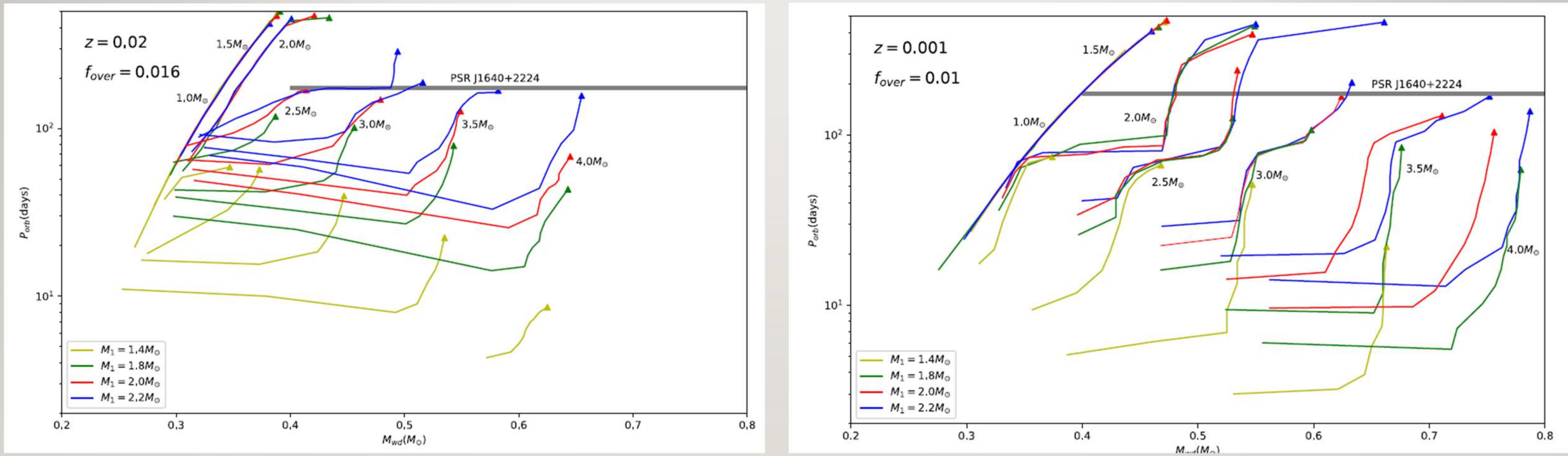


Figure 1. Final orbital period as a function of WD mass. The gray, solid horizontal line represents the distribution of the orbital period and the WD mass for PSR J1640+2224. The triangles are used to distinguish different curves that overlap. In the left and right panels we adopt different chemical compositions and overshooting parameters.

Possible results

Table 1: Final results of orbit period $170 \leq P \leq 180$ days and WD mass $M_{WD} \geq 0.4 M_\odot$

M_1^{ini} ($M_\odot$) (1)	M_2^{ini} ($M_\odot$) (2)	P_{orb}^{ini} (days) (3)	t_{RLO} (Myr) (4)	Case (5)	M_1^{fin} ($M_\odot$) (6)	M_2^{fin} ($M_\odot$) (7)	P_{orb}^{fin} (days) (8)	Type (9)	ΔM_1 ($M_\odot$) (10)	$\Delta t_{\dot{M}}$ (Myr) (11)	$\dot{M}_{max}$ ($M_\odot yr^{-1}$) (12)
Population I ($X = 0.7$, $Z = 0.02$)											
2.0	2.5	5.35	597.9	B	2.109	0.414	170	HeCO	0.109	5.845	3.16×10^{-4}
2.2	2.5	7	598.596	B	2.304	0.488	175	CO	0.104	6.58	5.01×10^{-6}
2.2	3	7	363.239	B	2.255	0.506	176.5	CO	0.055	3.363	7.94×10^{-6}
2.2	3.5	10.8	241.819	B	2.226	0.571	171.5	CO	0.026	1.558	2.51×10^{-5}
2.25	4	15.2	170.965	B	2.266	0.634	170.8	CO	0.016	0.857	6.31×10^{-5}
Population II ($X = 0.75$, $Z = 0.001$)											
1.4	1.5	17	1557.870	B	1.837	0.400	173.9	He	0.437	27.950	3.16×10^{-7}
1.8	1.5	12.5	1547.698	B	2.427	0.400	175.4	He	0.627	38.912	7.59×10^{-8}
1.8	2.0	12	642.987	B	2.046	0.479	171.4	CO	0.246	13.62	1.58×10^{-6}
2.0	1.5	11.5	1544.370	B	2.694	0.400	178.3	He	0.694	42.240	5.89×10^{-8}
2.0	2.0	10.5	650.153	B	2.293	0.484	174.1	CO	0.293	16.379	5.01×10^{-7}
2.0	2.5	10.5	370.271	B	2.110	0.525	174.3	CO	0.110	6.503	7.94×10^{-6}
2.02	3.0	15	240.216	B	2.081	0.616	173.6	CO	0.061	4.134	3.98×10^{-5}
2.2	1.5	10.5	1540.127	B	2.965	0.400	176.9	He	0.756	46.617	4.37×10^{-8}
2.2	2.0	9	648.640	B	2.524	0.484	170.7	CO	0.324	13.085	3.16×10^{-7}
2.2	2.5	8.5	369.724	B	2.32	0.525	173.2	CO	0.12	7.045	6.31×10^{-6}
2.2	3.0	12.3	240.006	B	2.265	0.619	178.3	CO	0.065	4.367	2.51×10^{-5}
2.2	3.5	19	169.025	B	2.246	0.723	177.3	CO	0.046	3.098	7.94×10^{-5}
2.2	4.0	25.5	125.904	B	2.231	0.794	170.0	CO	0.031	1.760	2.00×10^{-4}

Note.—Col.(1): the initial mass of neutron star ($M_\odot$). Col.(2): the initial mass of donor star ($M_\odot$). Col.(3): initial orbital period (days). Col(4): the age of donor star at the onset of Roche lobe overflow (RLO) (Myr). Col(5): different cases of RLO. Col(6): the final mass of the NS ($M_\odot$). Col(7): final mass of the WD ($M_\odot$). Col(8): final orbital period (days). Col(9): final type of WD (He, HeCO, and CO WD, respectively). Col(10): the mass of matter accreted by a neutron star after the mass transfer phase ($M_\odot$). Col(11): the duration of the mass transfer phase (yr). Col(12): the maximum mass transfer rate($M_\odot$ yr^{-1})

Further Constraints from Spin Evolution

The spin-up rate of the NS in an LMXB is determined by the rate of angular momentum transfer due to mass accretion.

$$2\pi I\dot{P}/P^2 = \dot{M}_1(GM_1R_1)^{1/2},$$

Here we have assumed that the NS's magnetic field has been decayed so much that the accretion disk can extend to the surface of the NS. The amount of accreted mass needed to produce a MSP can be roughly estimated to be

$$\Delta M \sim 0.1 M_\odot (M_1/2M_\odot)^{1/2} (R_1/10^6\ \mathrm{cm})^{-1/2} (P/3\ \mathrm{ms})^{-1}.$$

The actual value of ΔM could be smaller by a factor of ~2 than that in this equation if considering the effect of the NS magnetic field–accretion disk interaction. Combing this with Table 1, we note that evolutions with Population II compositions seem to be more preferred for the formation of PSR J1640+2224.

Conclusions

We summary our mainly results as follows,

- For Population I chemical compositions, when $M_1 \cong 2.0 M_{\odot}$, it is possible to simultaneously account for the WD mass (~0.4 $M_{\odot}$) and the orbital period (~175 days). But if the WD mass>0.6 $M_{\odot}$, the NS mass should be larger than 2.2 $M_{\odot}$, and the donor star must initially be intermediate-mass.

- For Population II chemical compositions, the evolution of original LMXBs containing a 1.4 $M_{\odot}$ NS and a 1.0 $M_{\odot}$ donor star may form PSR J1640+2224-like binaries with a 0.4 $M_{\odot}$ WD companion. However, if the WD indeed has a mass higher than 0.6 $M_{\odot}$, then the initial NS mass should be no less than 2.0 $M_{\odot}$, and the initial donor mass should be higher than 3.0 $M_{\odot}$.

- When the NS spin evolution is taken into account, the evolutions with Population II compositions seem to be more preferred for the formation of PSR J1640+2224.

谢谢大家！