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Eccentric millisecond pulsars by resonant convection

by

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IA-FORTH Journal Club discussion
Heraklion, Greece, 28 January 2022

SKINAKAS
OBSERVATORY

Red Giant evolution

- Mass-radius relation $$r_{\rm env} \propto \left(\frac{L}{T_{\rm eff}^4}\right)^{1/2} \propto m_{\rm core}^{9/2}$$
- Mass-period relation $$P \propto \left(m_{\rm core}^{-1/3} r_{\rm env}\right)^{3/2} \propto m_{\rm core}^{25/4} \approx m_{\rm core}^{6}$$

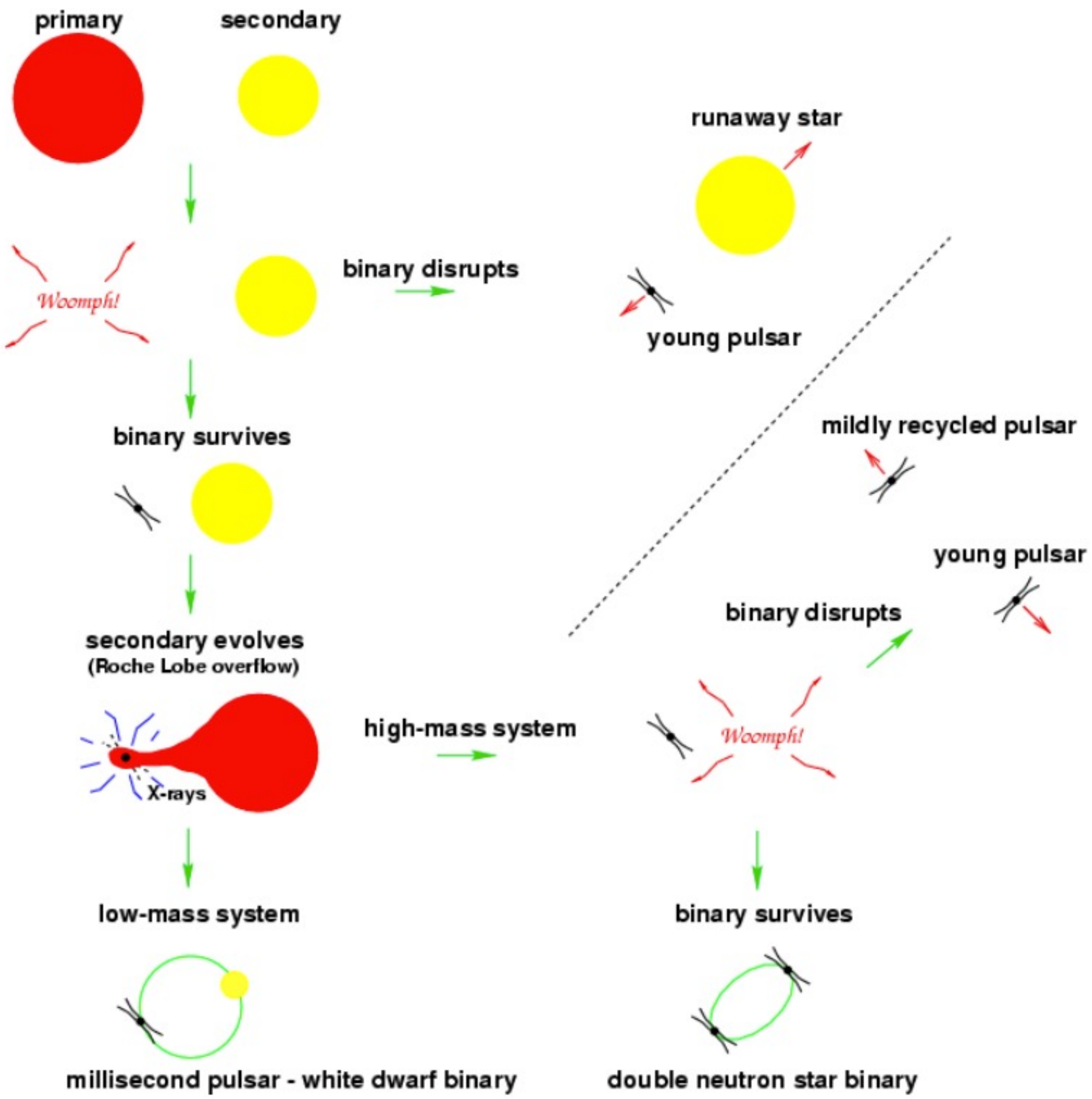
Eccentricity

- Eddy turnover time $$t_{\rm eddy} \sim \frac{r_{\rm env}}{v_{\rm eddy}}$$
- Circularization time-scale $$t_{\rm circ} \sim t_{\rm eddy}\frac{E_e}{E_{\rm tide}} \sim t_{\rm eddy}\frac{m_{\rm core}}{m_{\rm env}}\left(\frac{m_{\rm core}}{M}\right)^2\left(\frac{a}{r_{\rm env}}\right)^8$$
- Final eccentricity $$e \propto \left(\frac{m_{\rm env}}{m_{\rm core}}\right)^{1/2} P^{1/3} v_{\rm eddy} \propto m_{\rm env}^{1/6} m_{\rm core}^{6} \propto P$$

HMXB: $\dot{\Omega}_{donor} < \dot{\Omega}_{orbit}$ → Darwin instability

LMXB: $\dot{\Omega}_{donor} > \dot{\Omega}_{orbit}$ → Tides synchronize, then circularize

Lorimer (2008)



The puzzle

- Circularization theory predicts e ~ 10^{-43}
- Observed eccentricities of conventional MSPs are small, but non-zero
- Recent years eMSPs with e ~ 0.1 have been discovered
- These eMSPs deviate strongly from the general *e* – P relation within a narrow range of orbital periods P ≈ 20 - 30 days

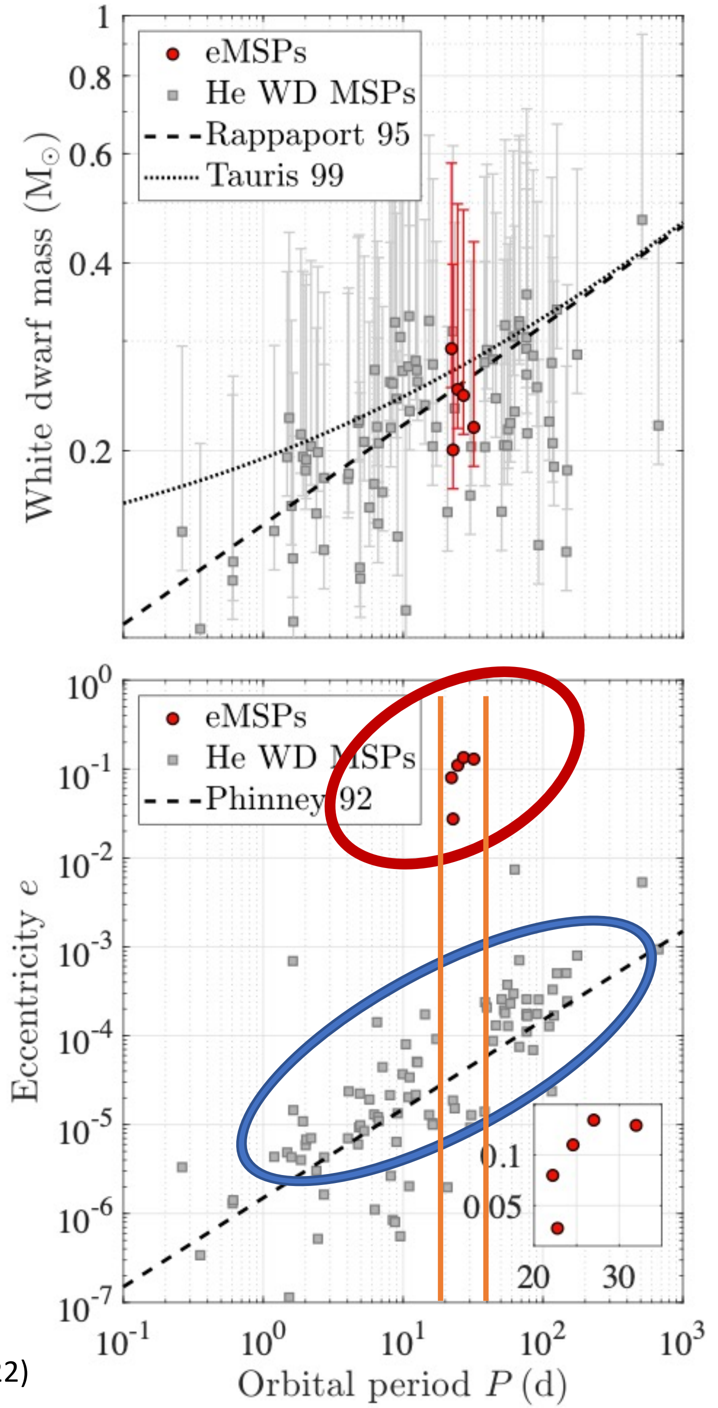
BUT

- Both MSPs and eMSPs follow the same mass-period relation

$$P \propto \left(m_{\rm core}^{-1/3} r_{\rm env}\right)^{3/2} \propto m_{\rm core}^{25/4} \approx m_{\rm core}^{6}$$

suggesting their common origin (RLOF of an RGB star with shell burning)

- Although residual eccentricities of MSPs can be explained (fluctuation-dissipation theorem; Phinney 1992), the existence of eMPSs poses a significant challenge



Ginzburg & Chiang (2022)

Alternative formation channels for eMSPs

Rotationally delayed accretion-induced collapse

Freire & Tauris (2014)

Predictions

- Low masses for the pulsar (1.22 – 1.31 Msun)
- Small spatial velocities for the binary

EXCLUDED (?)

Neutron star to strange quark star

Jiang et al. (2015)

Predictions

- Requires high densities → NS > 1.8 Msun

EXCLUDED (?)

Interactions with circumbinary disk

Antoniadis (2014)

Predictions

- Pulsar masses and systemic velocities similar to conventional MSPs
- Maximum P_{orb} for eMSPs corresponds to maximum mass for He WDs that undergo flashes
- Maximum value for the eccentricity
- Smaller eccentricities possible within P_{orb} gap

Observations

- Mass measurements (e.g. PSR J1946+3417, PSR J2234+0511) seem to contradict RD-AIC & strange star scenarios
- CBD scenario so far seems to be consistent with all observations

Eccentricity maintened by convection

Fluctuation-dissipation theorem: turbulent density fluctuations in the donor's convective envelope prevent perfect circularization of the orbit (Phinney 1992)

$$e \propto \left(\frac{m_{\rm env}}{m_{\rm core}}\right)^{1/2} P^{1/3} v_{\rm eddy} \propto m_{\rm env}^{1/6} m_{\rm core}^{6} \propto P$$

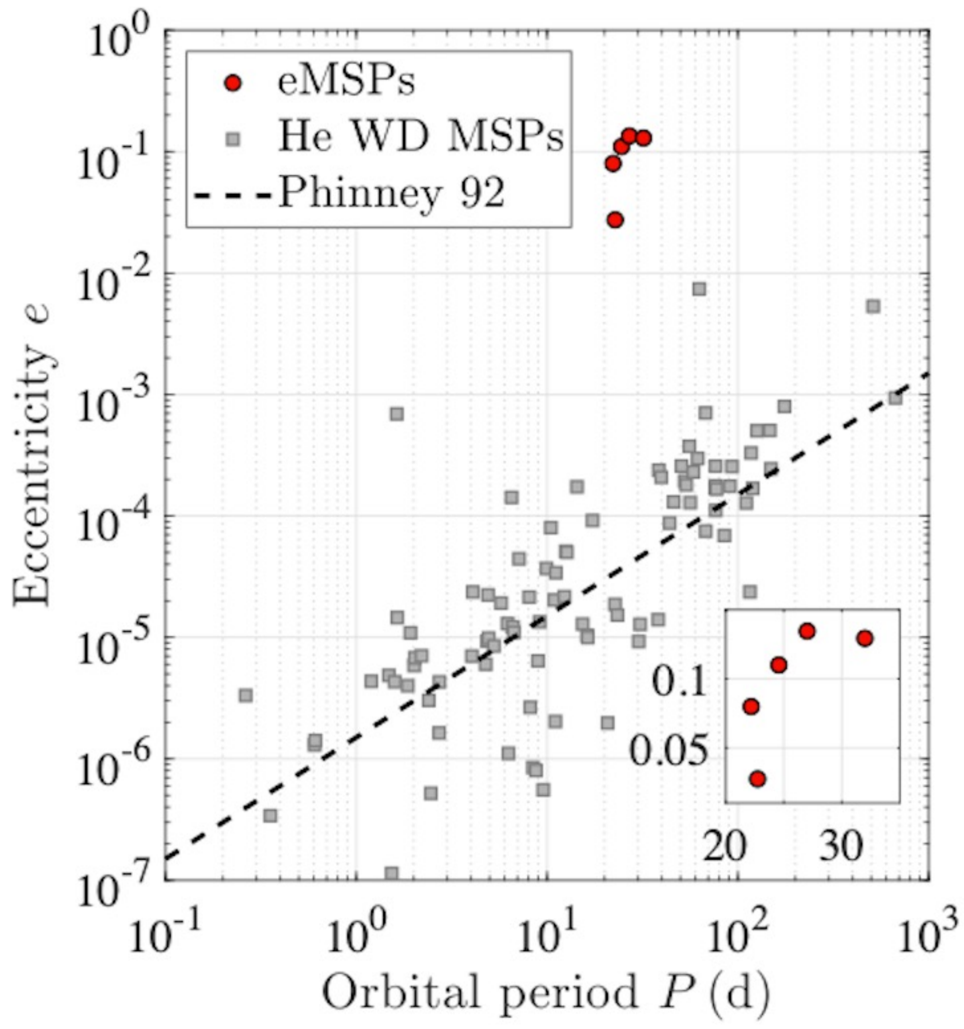
This explains well the observations for conventional MSPs except for the anomalous eMSPs, which cluster at P ≈ 20 - 30 days

Resonance: Orbital period equals the eddy's turnover time ($P \sim t_{eddy}$). For RGB stars t_{eddy} ≈ 25 days, **exactly where the eMSPs are being found**

Ansatz

At resonance eddies do not randomly change direction. Instead they form long-lived vortices generating a quadrupole moment that oscillates coherently and not stochastically → supported by 3D simulations of rotating RGB stars when $Ro \equiv \frac{P_{spin}}{t_{eddy}} \sim 1$

Ginzburg & Chiang (2022)



Eccentricity enhancement by resonant convection

Results (in a nutshell)

- ✓ Assuming the eddies coherently perturb the orbit over t_{circ}, the eccentricity at resonance is enchanced by a factor of

$$\frac{e^{\rm res}}{e} = \frac{v_e^{\rm res}}{v_e} \sim \left(\frac{t_{\rm circ}}{t_{\rm eddy}}\right)^{1/2} \sim \left(\frac{t_{\rm nuc}}{P}\right)^{1/2} \approx 3 \times 10^3$$

On Hayashi track, H^- opacity depends strongly on metallicity; Different compositions lead to $\frac{\Delta T_{eff}}{T_{eff}} \approx 0.3$ (Kippenhahn et al. 2012)

Since $t_{eddy} \sim \left(\frac{m_{env}}{\sigma T_{eff}}\right)^{1/3} \rightarrow \frac{\Delta P}{P} \approx 0.4$

- ✓ The spread in observed eMSPs orbital periods can be explained from variations in t_{eddy} due to different metallicities
- ✓ These variations broaden the range of resonant P but also leave systems out of resonance

Ginzburg & Chiang (2022)