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The formation of the magnetic symbiotic star FN Sgr

Diogo Belloni[1], Joanna Mikołajewska[2], & Matthias R. Schreiber[1,3]

[1] Departamento de Física, Universidad Técnica Federico Santa María, Av. España 1680, Valparaíso, Chile
e-mail: diogobellonizorzi@gmail.com
[2] Centrum Astronomiczne im. Mikołaja Kopernika, ul. Bartycka 18, 00-716 Warszawa, Poland
[3] Millenium Nucleus for Planet Formation, Valparaíso, Chile

Abstract. There are several symbiotic stars (e.g. BF Cyg, Z And, and FN Sgr) in which periodic signals of tens of minutes have been detected. These periods have been interpreted as the spin period of magnetic white dwarfs (WDs) that accrete through a magnetic stream originating from a truncated accretion disc. To shed light on the origin of magnetic symbiotic stars, we investigated the system FN Sgr in detail. We found that FN Sgr can be reasonably well explained assuming that its WD was formed through common-envelope (CE) evolution and that the magnetic field of its WD was generated by the rotation- and crystallization-driven dynamo. We conclude that this scenario, or any age-dependent scenario, can consistently explain the origin of magnetic symbiotic stars. This adds another piece to the pile of evidence supporting this scenario. If our formation channel is correct, our findings suggest that WDs in most symbiotic stars formed through CE evolution might be magnetic, provided that the red giant has spent $\gtrsim$ 3 Gyr as a main-sequence star.

Resumo. Existem várias estrelas simbióticas (e.g., BF Cyg, Z And e FN Sgr) nas quais sinais periódicos de dezenas de minutos foram detectados. Esses períodos têm sido interpretados como os períodos de rotação de anãs brancas (WDs) magnéticas que acretam massa por meio de um fluxo magnético originário de um disco de acreção truncado. Para lançar luz sobre a origem das estrelas simbióticas magnéticas, investigamos o sistema FN Sgr em detalhes. Descobrimos que FN Sgr pode ser razoavelmente bem explicado assumindo que sua WD foi formada por meio de evolução de envelope comum e que o campo magnético de sua WD foi gerado pelo dínamo impulsionado por rotação e cristalização. Concluímos que esse cenário, ou qualquer cenário dependente da idade, pode explicar consistentemente a origem das estrelas simbióticas magnéticas. Isso adiciona outra peça à pilha de evidências que apoiam esse cenário. Se nosso canal de formação estiver correto, nossas descobertas sugerem que as WDs na maioria das estrelas simbióticas formadas por evolução de envelope comum podem ser magnéticas, desde que a gigante vermelha tenha passado $\gtrsim$ 3 bilhões de anos como uma estrela da sequência principal.

Keywords. methods: numerical – stars: binaries: symbiotic – stars: evolution – stars: individual: FN Sgr – stars: magnetic field – white dwarfs

1. Introduction

Symbiotic Stars (SySts) are interacting binaries in which, in most cases, a white dwarf (WD) accretes matter from an evolved red giant (RG) donor, which can be a first giant branch (FGB) star or an asymptotic giant branch (AGB) star (e.g., Mikołajewska 2012). Their orbital periods are typically between a few hundred days and a few thousand days, but it can also be tens of years if the RG is a Mira-like variable. Recent indirect evidence indicates that some SySts contain strongly magnetic WDs (e.g., Merc et al. 2024, and references therein). Analysing the formation history of SySts can therefore provide additional constraints on the generation of WD magnetic fields.

Among the several scenarios that have been proposed so far to explain the origin of magnetism in WDs, the crystallization scenario is currently the most promising one. After a carbon–oxygen WD is formed, it begins to age and cool down and when its temperature is sufficiently low, its inner region starts to crystallize and the crystallized mass fraction grows with time. Crystallization leads to a solid oxygen-rich core surrounded by a liquid carbon-rich convective mantle, a configuration that can maintain a magnetic dynamo, similar to those assumed to generate the magnetic fields of planets, proto-stars and M dwarfs (Christensen et al. 2009). The idea that the onset of crystallization in WDs generates convection which then might drive a dynamo was first proposed by Isern et al. (2017) as an explanation for weak magnetic fields ($\lesssim$ 0.1 MG) but only gained considerable attention when Schreiber et al. (2021) showed that several problems of WD binary evolution can be solved if the dynamo is able to produce strong magnetic fields (> 1 MG).

We showed that we can explain the origin of magnetism in magnetic SySts with the rotation- and crystallization-driven dynamo. We focused our efforts on FN Sgr, as this object is the SySt with the strongest evidence for hosting a magnetic WD (Magdolen et al. 2023). Its orbital period of ~ 567 d was derived by Brandi et al. (2005), based on long-term photometric data over 30 years. The donor star in FN Sgr is an M 5-type RG of mass ~ 1.3 $M_\odot$ and the accreting WD has a mass of ~ 0.6 $M_\odot$. We carried out binary models with the MESA[1] code (Jermyn et al. 2023, and references therein) and found that the properties of FN Sgr can be explained reasonably well through CE if the detailed evolution of the thermally-pulsing AGB (TP-AGB) phase is taken into account. The origin of the magnetic field of its WD is consistent with the crystallization dynamo scenario. Here, we present a summary of this work, which was published in Belloni, Mikołajewska, & Schreiber (2024).

2. Formation Pathway for FN Sgr

We found that a binary with zero-age main-sequence masses of ~ 2.2 and ~ 1.36 $M_\odot$ and orbital period of ~ 2000 d, evolves to the required initial post-CE binary to explain FN Sgr. A non-magnetic WD is first formed through CE evolution when the

[1] For reference, interested readers can access the MESA files that we made available at https://zenodo.org/records/10937460.

Table 1. Main predicted and observed parameters of FN Sgr (Belloni, Mikołajewska, & Schreiber 2024).

Parameter	Observed	Predicted
orbital period (d)	567.3 ± 0.3	567.31
separation ($R_\odot$)	358 ± 19	359.52
mass transfer rate (10^{-8} $M_\odot$ yr^{-1})	2.6 – 5.2	4.44
RG radius ($R_\odot$)	150^{+15}_{-15} – 161^{+13}_{-9}	145.96
RG mass ($M_\odot$)	1.33 ± 0.24	1.331
WD mass ($M_\odot$)	0.60 ± 0.09	0.606

more massive star in the binary fills its Roche lobe as a TP-AGB star. The companion of the WD in the resulting post-CE binary evolves and becomes a sub-giant. Meanwhile, the WD ages and begins to crystallize, which creates the conditions for a weak magnetic field to be generated. The magnetic field initially remains deep inside the core but eventually, after a few hundred million years, diffuses and penetrates the surface, becoming detectable. In the meantime, the sub-giant star evolves, becomes an evolved FGB star, and starts to transfer some mass and angular momentum through stellar winds to the WD. As a result of the angular momentum accretion, the WD spin period decreases to minutes, and its magnetic field reaches the super-equipartition regime and is amplified, according to the rotation- and crystallization-driven dynamo. Subsequently, the binary evolves to a SySt, hosting a magnetic WD that is accreting matter through atmospheric Roche-lobe overflow.

We show in Fig. 1 the post-CE evolution from around the moment the binary becomes a SySt up to the onset of the second CE evolution. We included the evolution of the orbital period, the mass transfer rate, and the RG mass, as these properties can be directly compared with those derived from observations. All predicted and observed values are in reasonably good agreement, as seen in Tab. 1.

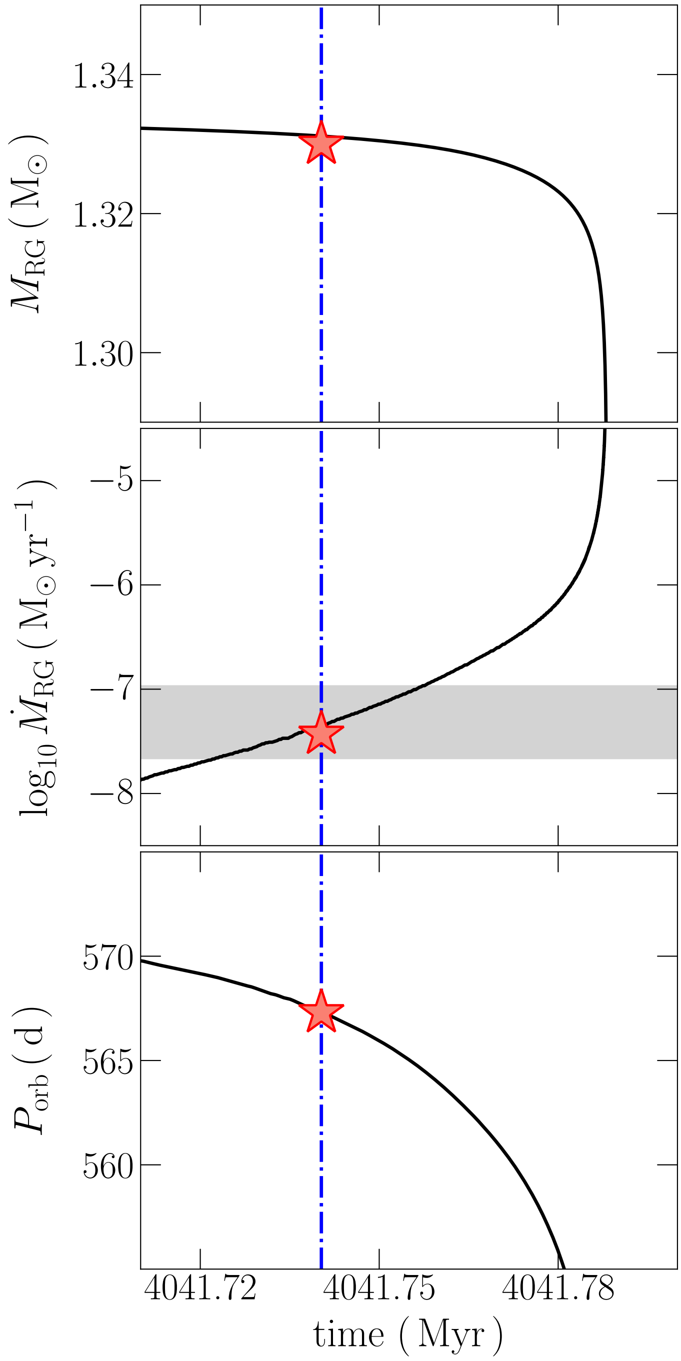

Figure 1. Post-CE evolution with time of the orbital period (P_{orb}), the mass transfer rate due to atmospheric Roche-lobe overflow ($\dot{M}_{RG}$), and the RG mass (M_{RG}). The star indicates the present-day properties of FN Sgr, without error bars, the rectangle the minimum and maximum mass transfer rate required to explain the WD luminosity as powered by nuclear burning, and the vertical line the time at which the binary has the same orbital period of FN Sgr. Our model reproduces reasonably well not only the RG mass and the orbital period but also the mass transfer rate.

3. Conclusions

We carried out binary evolution with the MESA code and investigated the origin of magnetic symbiotic stars. Our results, published in Belloni, Mikołajewska, & Schreiber (2024), support the idea that a crystallization-driven dynamo is responsible for the generation of magnetic fields in WDs. Despite that, theoretical issues, such as the diffusion timescale and the appropriate scaling law for determining the field strength still need to be solved.

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