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Hydrodynamical simulations on state transitions in spider systems

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Spider systems represent a unique category of binaries featuring rotation-powered millisecond pulsars orbiting low-mass stellar companions within short periods, ranging from a few hours to a day. The growing number of known sources, particularly through multiwavelength follow-up investigations of unidentified Fermi sources, has revealed a subset known as transitional millisecond pulsars (tMSPs). These tMSPs exhibit a fascinating phenomenon in which the neutron star (NS) transitions between a radio pulsar state and a faint low-mass X-ray binary state over the course of a few years. This unique behavior provides a rare opportunity to unravel the interplay between winds and the recycling scenario central to the formation of millisecond pulsars. Employing an Adaptative Mesh Refinement (AMR) code we perform 2D hydrodynamical (HD) simulations that consider the impact of gravity and orbital motion on the interaction between the flows from both stars. By exploring the mass loss and launch speed of the winds, we successfully recreate two phenomenologically distinct regimes: the accretion stream and the pulsar radio state. We identify a tipping point that marks the sharp transition between these two states. Furthermore close to this tipping point we observe an unstable behavior prone to multiple transitions. Our study sheds light on the crucial roles played by gravity and momentum ratio in shaping the diverse evolutionary phases observed in transitional millisecond pulsars. This research significantly contributes to a deeper understanding of the intricate behaviors exhibited by these captivating celestial objects.

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1. Introduction

In recent years, there has been notable progress in understanding the spider pulsars binary systems known as "redbacks" (RBs) and "black widows" (BWs) [1, 2]. These systems hosts rotation-powered millisecond pulsars within compact binary orbits, typically featuring short orbital periods, $P_{\rm orb} \leq 1$ day [3]. The pulsar and its companion are close together at about $a_{\rm IB} \sim 10^{11}$ cm from each other. The mass of the companion varies, with BWs having stars of around 0.01 to 0.05 $M_{\odot}$, and RBs having non-degenerate evaporating companions with masses ranging from about 0.1 to 0.5 $M_{\odot}$ [3]. More than 90 spider systems have been discovered over the last decade thanks to follow-up observations of Fermi/LAT unidentified sources [e.g. 4–6], providing valuable insights into their properties and characteristics.

A subclass of millisecond pulsars (MSPs), known as transitional millisecond pulsars (tMSPs) (PSR J1023+0038 [7], PSR J1824-2452I [8], PSR J1227-4853 [9]) has recently emerged. These remarkable systems undergo rapid transitions between the radio pulsar and accretion states over timescales of a few years. This poses significant challenges as the underlying mechanisms governing the evolution of these celestial objects are not yet fully understood. The first tMSP discovered was PSR J1023+0038 [7]. Initially, optical observations in 2001 led to the misclassification of the previously identified radio source as a cataclysmic variable with an accretion disk. This classification was based on the detection of double-peaked emission lines [10]. However, by 2004, the emission lines had vanished and radio pulsations were detected, leading to the re-evaluation of the source as a radio pulsar [7, 11]. Remaining in the radio pulsar state until 2013, PSR J1023+0038 [12] underwent a new transformation when its radio pulsations ceased. This transition was accompanied by a remarkable increase in optical/UV, X-ray, and γ-ray activity, indicating a reactivation of accretion. The transition took place within less than two weeks [13] and the system has since remained in this state. The intriguing and dynamic changes observed in spider systems can be attributed to the delicate balance between the ram pressure exerted by the pulsar wind on the matter lost by the low-mass companion and the gravitational and rotational forces shaping the flow of stellar matter [14].

Here we use 2D hydrodynamical numerical simulations to investigate the wind-wind interaction within the equatorial plane between the pulsar wind and the stellar wind of the low-mass companion. Considering the transitional nature of tMSPs, our focus is on the parameter space around the boundary between accreting and non-accreting behaviour.

2. Physical and numerical model

In this study, we have chosen to investigate the case of a RB system that is prone to transitional behaviour. We consider a pulsar with a mass of $M_{\rm psr} = 1.4 M_{\odot}$ and a companion star with a mass of $M_{\rm c} = 0.4 M_{\odot}$. Their separation distance is set at $a_{\rm IB} = 10^{11}$ cm, corresponding to a revolution time of $P = \frac{4\pi^2 a_{\rm IB}^3}{G(M_{\rm psr}+M_{\rm c})} \approx 1.28 \times 10^4$ s (equivalent to 3.56 hours). The center of mass of the system is located at a distance of $a_{\rm center} \approx 0.77 a_{\rm IB}$ from the companion star. For our model, we assume that both the pulsar and companion winds are non-magnetized, isotropic, supersonic, and originate from the surface of spheres surrounding each object. Each wind mechanical luminosity L_w, mass flux

$\dot{m}_w$, and speed v_w are related by the conservation of mechanical power as kinetic energy, expressed as $L_w = \dot{m}_w v_w^2/2$.

The pulsar wind emanates from the surface of a sphere with a radius of $R_{\rm psr,w} = 0.025a_{\rm IB}$. We set the pulsar spin-down luminosity to $L_{\rm sd} = 10^{35}$ erg/s, a typical value for known transitional millisecond pulsars (tMSPs), where the mechanical luminosity $L_{\rm psr} = 0.9L_{\rm sd}$. The pulsar wind is considered non-relativistic with a speed $v_{\rm psr} = c/30 = 10^4$ km/s with c the speed of light. The mass flux is chosen so that the momentum flux of the wind $\dot{m}_{\rm psr}v_{\rm psr} = L_{\rm psr}/c$ effectively reproduces that of the actual ultra-relativistic wind.

The companion wind is fully characterized by the stellar mass loss $\dot{m}_{\rm c}$ and speed $v_{\rm c,w}$. In the following, we investigate the effects of varying these parameters. The mass-loss rate is constrained by stellar evolution considerations to remain below $\dot{m}_{\rm c,max} = 10^{-8}{\rm M}_\odot{\rm yr}^{-1}$ [3, 15]. The wind speed is set to prevent the transferred matter from escaping the system, ensuring its capture by the pulsar's gravitational field and facilitating an accretion process through Roche lobe overflow (RLOF). The wind emanates from the equipotential surface at $R_{\rm c,w} = 0.3a_{\rm IB}$ along the line of centers, such that the Roche lobe filling ratio depends on $R_{\rm c,w}$. Additionally, we consider the effect of heating the companion's wind upstream by the pulsar's γ-ray luminosity $L_\gamma = 0.1L_{\rm sd}$.

3. Simulation Setup

In this study we use the Message Passing Interface-Adaptive Mesh Refinement Versatile Advection Code (MPI-AMRVAC; [16]). We implement a rotating frame treatment around the center of mass and solve the conservation equations for mass, momentum, and energy. The effects of gravity from both stars, reference frame rotation and heating induced by the pulsar wind were taken into account.

The simulations are conducted on a 2D polar grid, covering a radial extent of $r = [3\times10^9, 2\times10^{11}]$ cm and a toroidal extent of $\phi = [0, 2\pi]$. In the radial direction, a logarithmic grid is employed. Initially, the grid is refined to the first level with a resolution of (32×64) cells. Due to the substantial scale difference between the shock scales, the pulsar wind zone, and the overall simulation box, adaptive mesh refinement (AMR) is crucial to accurately resolve significant variations in such system. In our simulations, the grid is allowed to be refined up to 9 additional levels, with a doubling of resolution at each new level of refinement. The refinement and coarsening processes utilized Lohner's error estimator to assess second-order variations in density and radial velocity. Moreover, refinement is only allowed in regions where the wind is encountered. The companion star is positioned at the grid center, and the pulsar is set at a distance $a_{\rm IB}$ from the center of the grid (on the right for the next figures).

4. Simulations of Radio Pulsar and Accretion Stream states

We present in Fig. 1 two simulations representing the two characteristic states of spider systems: Radio Pulsar (RP) and Accretion Stream (AS). The initial speeds are set at $v_{\rm c,w} = 100$ km/s and $v_{\rm c,w} = 200$ km/s, respectively. Notably, the mass flux is consistent between both simulations, maintained at $\dot{m}_{\rm c} = 9\times10^{-10}{\rm M}\odot/{\rm yr}$.

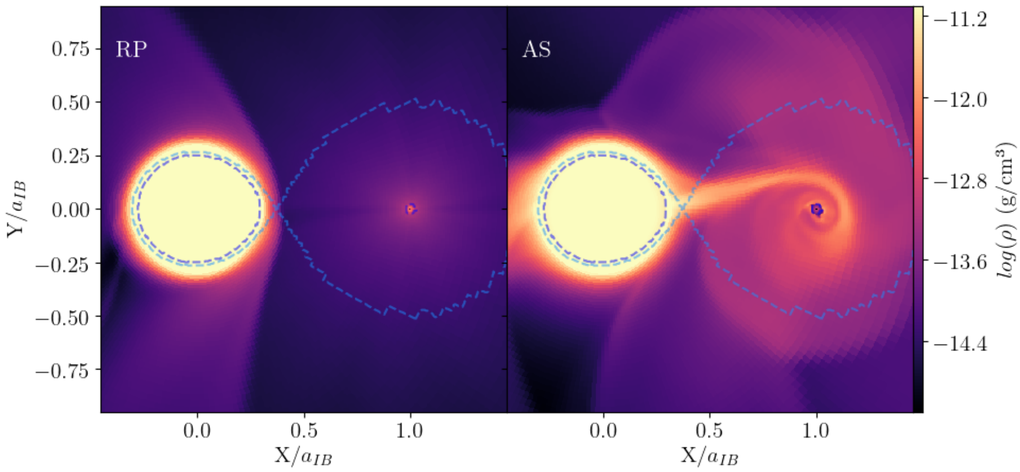

Figure 1: Two potential outcomes determined by companion wind parameters. In the left panel, the stationary Radio Pulsar (RP) state is depicted, characterized by the presence of an Intra-Binary Shock (IBS) near the companion surface, preventing matter from accreting onto the NS. In the right panel, the Accretion Stream (AS) state is illustrated, where the accretion stream successfully reaches and encircles the NS.

In the RP simulation the pulsar wind is dominant, the formation of the accretion stream is prevented and the system thus remains in the radio pulsar state as there is no matter around the NS to obstruct the radio emission. This state is notably stationary, and the Intra-Binary Shock (IBS) formed exhibits minimal variation. The IBS in spider systems is known to exhibit a distinctive feature in the X-ray light curve, an orbital variability with a characteristic double-peak emission pattern. This phenomenon is usually interpreted as a consequence of the beaming effect experienced by particles moving in two main directions along the shock [17, 18]. We have constructed the corresponding X-rays light curve obtained by the synchrotron radiation that occurs within the shocked material. This results in a distinct double-peak feature around the star's inferior conjunction, not perfectly centered due to the asymmetry of the shock surrounding the companion introduced by the orbital motion. We also found that the presence of the companion star in the line of sight leads to eclipses in the received flux, providing a new perspective on the characteristic shape of the X-ray light curve of spider systems. More details will be given in a forthcoming publication.

In the case of the AS simulation, the specific characteristics of the companion wind lead to the overflow of gas and an accretion stream directed towards the NS emerges. Indeed doubling the initial speed of the companion wind increases the available matter for accretion, enhancing the density within the stream. The ram pressure is consequently increased, inducing a dominance of the accretion stream over the pulsar wind. Upon reaching the NS, the accretion stream is expelled and pushed away, creating a shock between the stream and the pulsar wind. As matter accumulates around the pulsar due to the constant injection of material from the companion there comes a point, due to the system's rotation, where the stream collides with itself after completing a full orbit around the NS. The system then transitions to an accretion stream state characterized by the formation of a residual disk from previous interactions spiraling inward towards the NS. This state notably exhibits matter in close proximity to the NS, blocking the potential radio emission from the pulsar. The simulation then reveals periods of instabilities, slighty shorter than the orbital period. If the accretion stream regime is not totally disrupted by the pulsar wind (see Sec. 5), we observe a quasi-stationary state, where the matter accumulating and revolving around the NS is intermittently pushed away, disrupting the continuous inflow of material from the accretion stream. Despite these disruptions, the system returns to the configuration depicted in the right panel of Fig. 1. Since the matter surrounding the NS is not entirely expelled during these instabilities, we consider the system to remain in the accretion stream state, with the emission of radio pulsations still obstructed. This instability highlights the intricate interplay between the accretion flow and the pulsar wind.

5. Tipping point of transition and unstable behavior

Importantly, the transition from dominance of one wind to another exhibits a sharp contrast to isotropic wind interaction by showing a distinctive discontinuity in the dominance of the winds. Either the accretion arm emerges or not. This behavior underscores the impact of gravity and the RLOF regime in determining the dominant wind.

In our unique scenario, where gravity and orbital motion significantly influence wind interaction, it becomes crucial to analyze the ram pressure within the accretion stream and compare it with the ram pressure of the pulsar wind. To do so we conducted simulations without the pulsar wind in order to characterize the undisturbed accretion stream. The transition radius, denoted as $r_{\rm t}$, marks the distance from the companion star where the ram pressures within the stream and the pulsar wind are equal, symbolized by the equation $\rho_{\rm c,w}(r_{\rm t})v^2_{\rm c,w}(r_{\rm t}) = \rho_{\rm psr,w}(r_{\rm t})v^2_{\rm psr,w}(r_{\rm t})$. Each ram pressure is calculated in the absence of the opposite wind.

The ram pressure within the stream increases with distance from the companion star. Since the ram pressure is higher with a strong companion wind, the stream becomes dominant over the pulsar wind at lower values of $r_{\rm t}$, affecting the outcome of the system (see left panel, Fig. 2). We introduce the concept of a critical radius, denoted as $r_{\rm crit}$, which determines the outcome of the system based on the transition radius $r_{\rm t}$, leading to two distinct scenarios. First, if $r_{\rm t} < r_{\rm crit}$ the accretion stream emerges as it becomes dominant soon enough, overcoming the pulsar wind ram pressure. This is the AS state. Second, if $r_{\rm t} > r_{\rm crit}$ the pulsar wind prevents the increase of stream ram pressure necessary for emergence. The system remains in the RP state.

This observation implies the existence of a tipping point where a rapid transition from a pulsar-dominant state to an accretion stream state occurs. We thus propose to compute the ratio η of ram pressure between the pulsar wind and within the accretion stream at the critical radius $r_{\rm crit}$:

$$\eta = \frac{\rho_{\rm c,\,w}(r_{\rm crit})\, v^2_{\rm c,\,w}(r_{\rm crit})}{\rho_{\rm psr,\,w}(r_{\rm crit})\, v^2_{\rm psr,\,w}(r_{\rm crit})}\,, \tag{1}$$

Examination of the position of the shock in different simulations reveals a clear tipping point. The shock occurs close to the surface of either the companion star or the NS (see right panel, Fig. 2), highlighting the significant transition the system is undergoing. This potential tipping point emerges as a plausible explanation for the observed transitional phenomena in spider systems, suggesting their close proximity to such a crucial point.

In support of this idea, we observe that near this tipping point, the system undergoes an unstable phase marked by the disruption of a previously established accretion stream state (see Fig. 3). The

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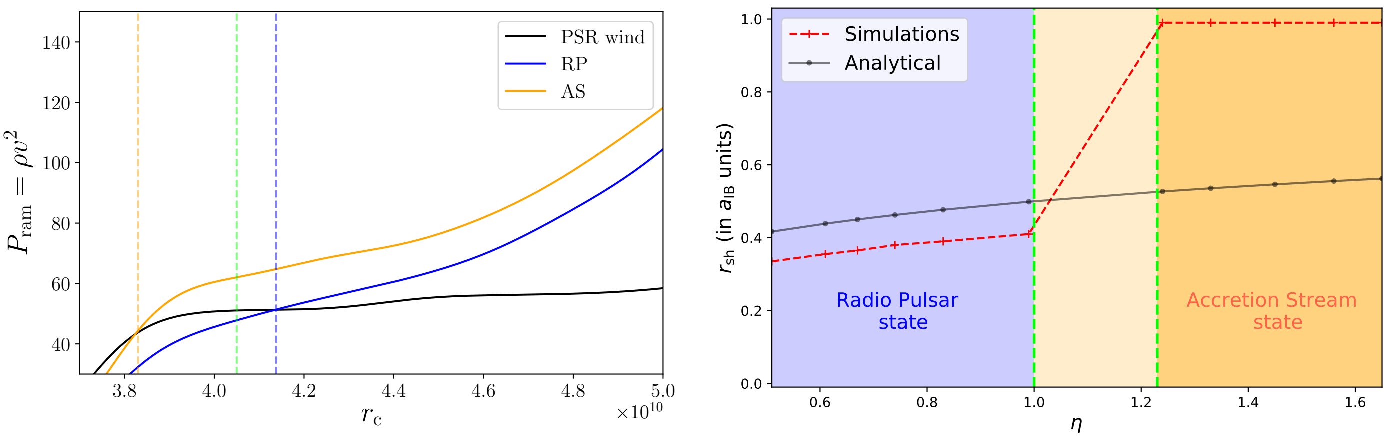

Figure 2: Left panel depicts the variation of ram pressure with distance from the companion star. The black curve represents the ram pressure of the pulsar wind, while the blue and orange curves depict the ram pressure within the accretion stream (for simulations conducted without a pulsar wind). Vertical blue and orange lines indicate transition radii ($r_{\rm t}$) where each accretion stream curve intersects with the 'PSR wind' curve. The vertical green line marks the critical radius $r_{\rm crit}$. If the accretion stream fails to become dominant quickly enough to emerge, $r_{\rm t} > r_{\rm crit}$, the system enters the RP state; otherwise if $r_{\rm t} < r_{\rm crit}$, the accretion stream emerges and the system transitions to the AS state.
Right panel shows the shock radius of the IBS formed between the winds as a function of the ratio η. Right part of the plot illustrates the AS state where the shock is occuring in close proximity of the NS at $r_{\rm sh} = 1$, while the left part shows the RP state with the shock occurring near the companion star surface $r_{\rm sh} = R_{\rm c} = 0.3$. In contrast to the smooth evolution expected from analytical models depicted by the black line, the abrupt change in radius highlights the tipping point of transition between the states. The unstable behavior depicted Fig. 3 occurs in systems with a ratio of $1<\eta<1.24$.

instabilities induced by the pulsar wind result in the expulsion of all matter surrounding the NS. Consequently, this state diverges from our defined AS state, as the radio emission is no longer obstructed. However, this unstable state is characterized by an intra-binary shock that exhibits less stability compared to the RP state. Considering the possible role of the accretion arm in absorbing or refracting radio emission, this phenomenon could offer an explanation for the unusually prolonged eclipses observed in spider systems. These eclipses, which are unusually long and go beyond what can be explained by the companion passing in the line of sight alone or by an evaporating companion, may find an intriguing explanation in this complex interplay. The system subsequently returns to an AS state after multiple orbital periods, only to undergo disruption once again.

6. Conclusion

In our investigation, we employed an AMR code to conduct 2D HD simulations, focusing on the intricate interaction between the winds of a stellar companion and a pulsar within a Redback (RB) system. Our objective was to differ from analytical approaches by creating a model that accounts for the influences of gravity, orbital motion and heating induced by the pulsar wind. By varying the parameters of the companion wind, we successfully replicated the two distinct states commonly observed in transitional systems. An accretion stream state for a dominating companion wind where we witness the emergence of an accretion stream steady enough to reach and encircle the NS. Conversely, a radio pulsar state where the accretion process is completely prevented due to its interaction with the pulsar wind. In contrast to analytical studies, our observations showed that the transition between these two states is not as gradual as expected, but exhibits a sudden shift at a specific tipping point. This tipping point, crucial to the transition, is determined by the dominance of the accretion stream over the pulsar wind. Moreover, close to this tipping point, we identified an unstable behavior marked by the intermittent creation and removal of the accretion stream. This transitional state, oscillating between the accretion and radio pulsar phases, provides a plausible explanation for the observed transitional phenomena in spider systems. It suggests that these systems may be situated in close proximity to the potentially existing tipping point. Our investigation has also shed light on the significant influence of the pulsar wind in perturbing the accretion stream regime. Across simulations with different companion wind parameters, the interaction between the accretion stream and the pulsar wind leads to the development of instabilities. In summary, our hydrodynamic approach has introduced a considerable level of complexity into the understanding of spider systems. We underscored that orbital motion and gravity are crucial factors shaping the observed interactions between the accretion stream and pulsar wind.

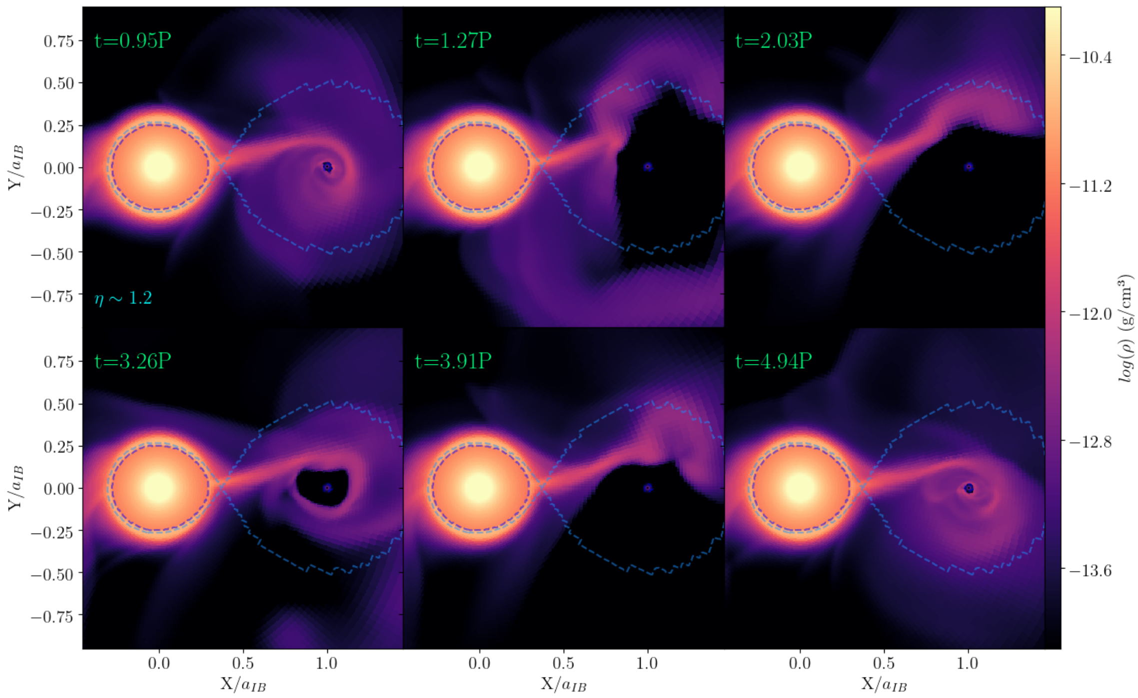

Figure 3: System exhibiting an unstable state prone to transitions for $\eta \sim 1.2$. The first panel illustrates the initial formation of the accretion stream state shortly after the simulation begins. However, this state is rapidly disrupted as the pulsar wind expels the accretion stream. This initiates a recurring pattern where the accretion stream attempts to fully encircle the NS and reconstruct itself. After multiple orbital periods, as depicted in the last panel, the system eventually retransitions to the Accretion Stream (AS) state before undergoing disruption once again.

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