Modelling Plasma Outflows in Compact Pulsar Binary Systems

Project level: Masters

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Background

Some millisecond pulsars exist in remarkably extreme binary systems where a rapidly spinning neutron star orbits a lightweight companion star within only a few hours. These pulsars emit powerful winds of energetic particles and radiation that continuously heat and strip material away from their companion stars. Because the pulsar gradually erodes its companion, these systems are popularly known as *Black Widow* and *Redback* pulsars.

The material escaping from the companion star does not simply disappear into space. Instead, it forms extended clouds and tails of ionized plasma that move around the binary orbit and evolve with time. The structure and dynamics of these plasma outflows are believed to be strongly influenced by orbital motion, pulsar wind pressure, gravity, and possibly magnetic field interactions.

Although many such systems have now been discovered, the detailed behaviour of the escaping plasma is still not fully understood. Questions such as how the plasma moves through the binary system, how dense the outflows become, how orbital motion shapes the plasma tails, and how these structures evolve over time remain active topics of research in compact binary astrophysics.

This project aims to explore these questions using computational simulations and orbital modelling techniques. By studying the dynamics of plasma outflows from ablated companion stars, the project seeks to build an intuitive physical picture of how complex plasma structures develop within compact pulsar binary systems.

Understanding how these plasma structures evolve is an important first step toward explaining the radio eclipses observed in many spider pulsar systems. By investigating how plasma clouds and tails form and move around the binary orbit, the project will help develop the physical foundation needed for future studies of eclipse formation and radio propagation effects in compact pulsar binaries.

Project statement

In this project, the student will investigate how plasma emitted from an ablated companion star evolves within compact pulsar binary systems.

The project focuses on so-called *Black Widow* and *Redback* pulsars, where energetic radiation and particle winds from a rapidly rotating millisecond pulsar continuously heat and strip material away from a lightweight companion star. The escaping material forms complex plasma outflows and trailing structures around the binary orbit whose dynamics are still not fully understood.

The student will begin by learning the basic physics of compact pulsar binaries, orbital motion, and plasma outflows in astrophysical systems. Using simplified computational models, the student will

simulate how particles emitted from the companion star move under the combined influence of orbital motion, gravity, and pulsar wind interactions.

A major component of the project will involve studying how different initial conditions and orbital configurations affect the evolution of plasma trajectories and outflow structures. The student will construct two-dimensional or three-dimensional visualizations of particle distributions and investigate how plasma tails and density structures evolve across the orbit.

Depending on project progress, the project may also include exploratory studies of how pulsar wind pressure or simplified magnetohydrodynamic effects influence the plasma morphology.

The student will:

- simulate particle trajectories within compact pulsar binary systems,
- model plasma outflows from ablated companion stars,
- investigate how orbital motion shapes plasma tails and density structures,
- study the evolution of particle distributions across the orbit,
- generate scientific visualizations of plasma morphology,
- and explore simplified pulsar wind interaction effects.

The project will primarily involve computational astrophysics, orbital dynamics, numerical simulations, and scientific visualization using Python-based modelling techniques.

Depending on project progress, the student may also explore simplified magnetohydrodynamic descriptions of plasma evolution in compact pulsar binaries.

Although the project will primarily focus on plasma dynamics and outflow morphology, understanding these particle distributions is an important step toward future investigations of radio eclipse behaviour in spider pulsar systems. The results of this work may therefore help provide physical insight into how plasma surrounding the binary system influences pulsar visibility during radio observations.

Scientific Scope of the Project

This project combines several active areas of modern astrophysics:

- pulsars and neutron stars,
- compact binary systems,
- plasma astrophysics,
- orbital dynamics,
- computational simulations,
- and scientific visualization.

Students will work on visually rich scientific problems involving plasma clouds, binary motion, particle dynamics, and orbital simulations, making this project both computationally engaging and physically intuitive.

Recommended skills and interests

The project is suitable for students interested in:

- astrophysics and compact objects,
- computational physics,

- orbital dynamics,
- plasma physics,
- numerical simulations,
- and scientific programming.

The analysis will primarily be carried out using Python and Linux-based scientific tools. Prior programming experience is helpful but not mandatory, as training will be provided during the project.

Students will gain experience in:

- computational modelling,
- numerical simulations,
- scientific visualization,
- astrophysical data interpretation,
- and modern research workflows used in astronomy.