NEUTRON STAR PULSARS AND POLARIZATION

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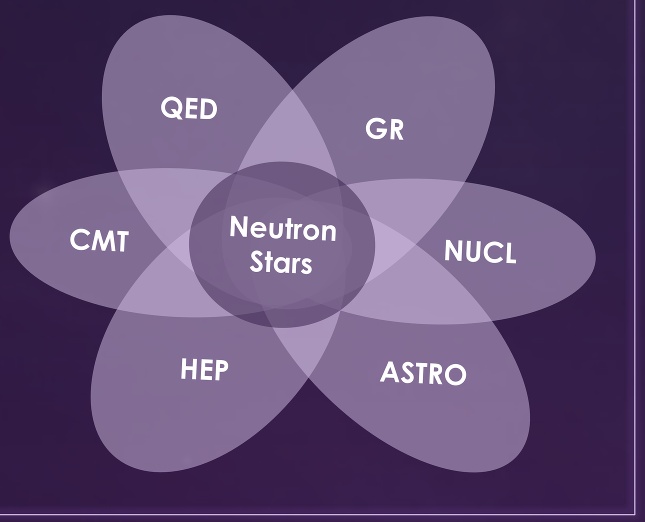
abstract

Polarization features of neutron star hints towards mechanisms producing the radiation. Several phenomena skew the polarization data before it reaches the observer. In our work, we ask – **given a pulsar configuration, what polarization data to expect from it (and vice versa)?**

introduction

Neutron Stars are Extreme Objects

Neutron stars (NS) are the cores of massive stars that survive through stellar supernova. They are the densest (~10^{17} kg/m^3) known objects in the universe (excluding blackholes) and produce the strongest known magnetic fields (~10^{12}-10^{13} G). Their extreme properties make them exotic astrophysical laboratories to test several domains of physics.



Pulsars Contain Polarization Information

Due to surface anisotropies, rotating neutron stars appear as point-sources with pulsating total flux (brightness summed across entire visible surface).

The way light waves orient themselves geometrically is known as its **polarization angle.** Since neutron stars produce 'polarized' emissions, applying specific polarization filters lead to different features in the pulsar observations.

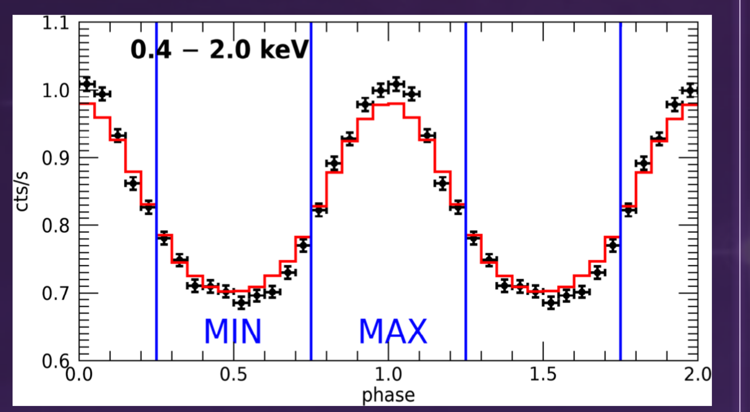


Fig: A pulsar observation of 'Calvera' pulsar as seen through ISS-NICER (Mereghetti et al 2021).

NS Attributes Affect Pulse Profiles

Features such as angle between magnetic and spin axis (η), angle between spin axis and line of sight (*i*), etc. characterize observed pulse profiles. Simulations help in understanding pulse profile dependencies and, with the help of Bayesian inference, extracting NS attributes from observational data.

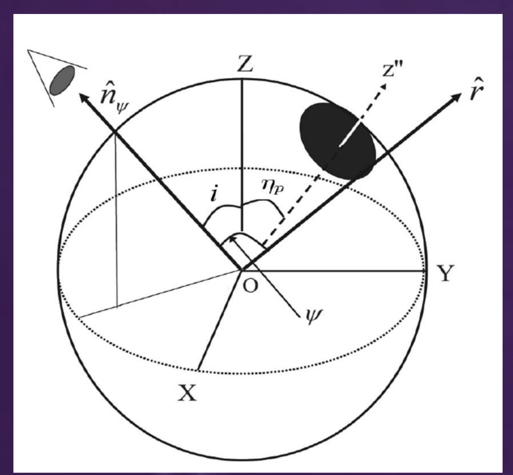


Fig: NS geometry (Mukherjee and Bhattacharya 2011).

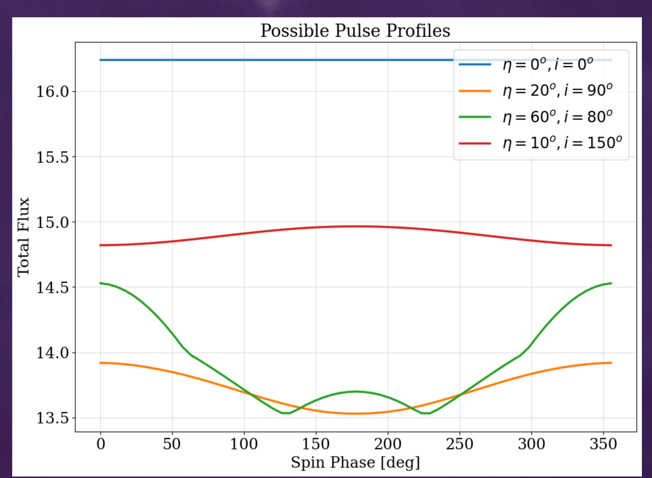
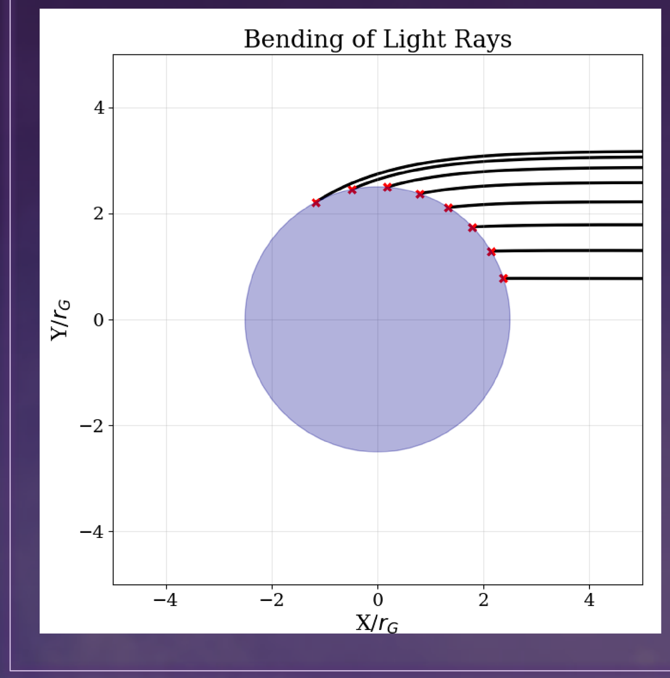


Fig: Simulated Pulse Profiles for varying NS geometries

problem

Gravitational Lensing Affects Polarization



As predicted by General Relativity (GR), strong gravity regimes near neutron stars bend light rays. This is known as **gravitational lensing** and it has two important effects-

We see more of the star at once. Surface patches hidden 'at the back' of the star become visible and contribute to the net polarization.

Polarization angle bends with light. Therefore, the polarization angle emitted through the surface is not what reaches the observer.

solution

Polarization Transport is Simulated

A modular code was developed to perform 'virtual observations' of objects from a catalogue of neutron stars with varying physical characteristics. The code includes GR effects and transports the polarization information to an observer at infinity, integrates over the entire visible surface and generates pulse profiles in desired stokes parameters. These observations can also be launched in parallel.

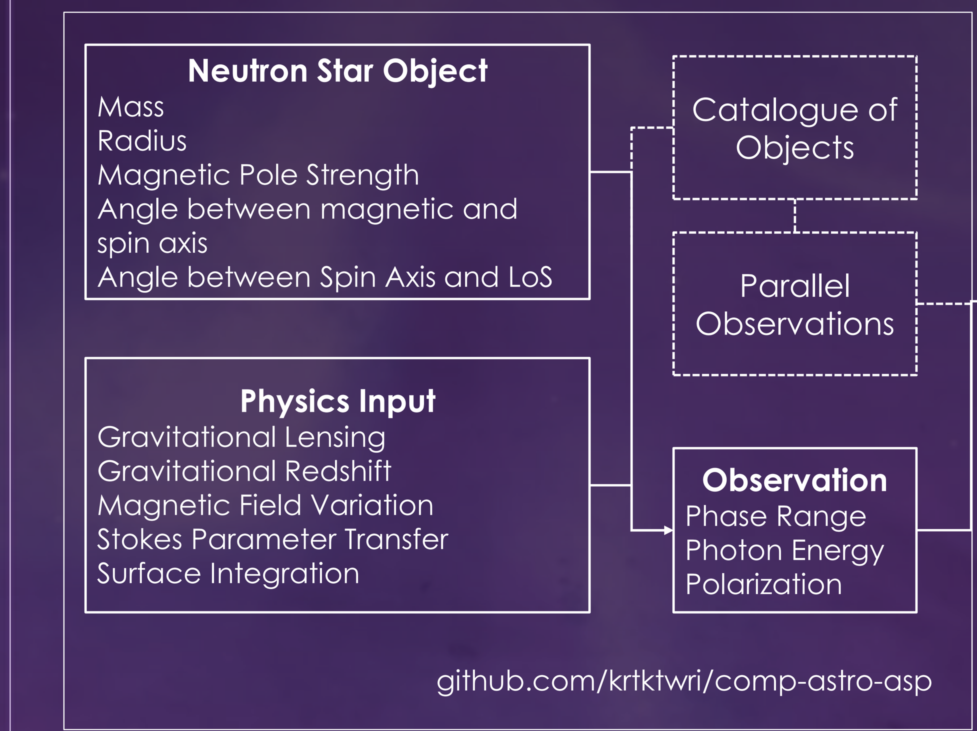
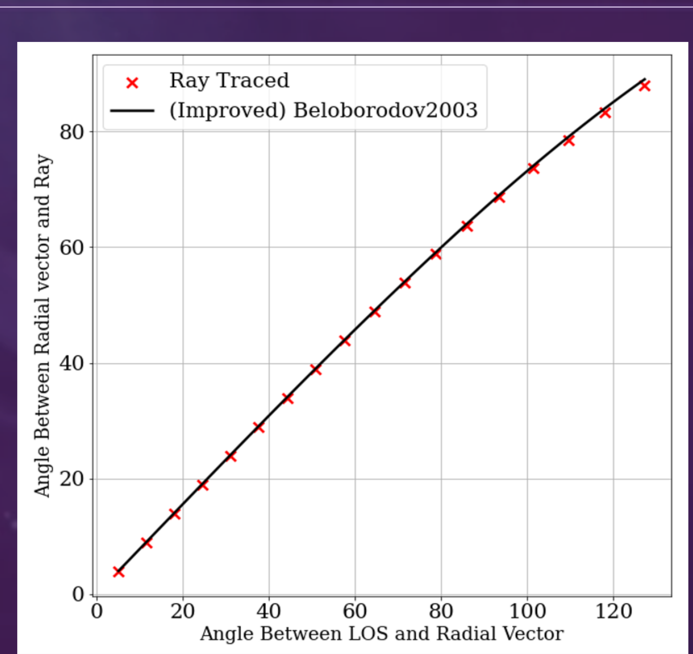


Fig: Flowchart representing various components of the polarization transport code

github.com/krtktwri/comp-astro-asp

Though light bending is well understood, tracing individual rays from every patch of the surface, for every time instance, is **computationally very slow**. Therefore, we use an approximation which connects the location of emitted ray on the star with the bending angle required to reach the observer.

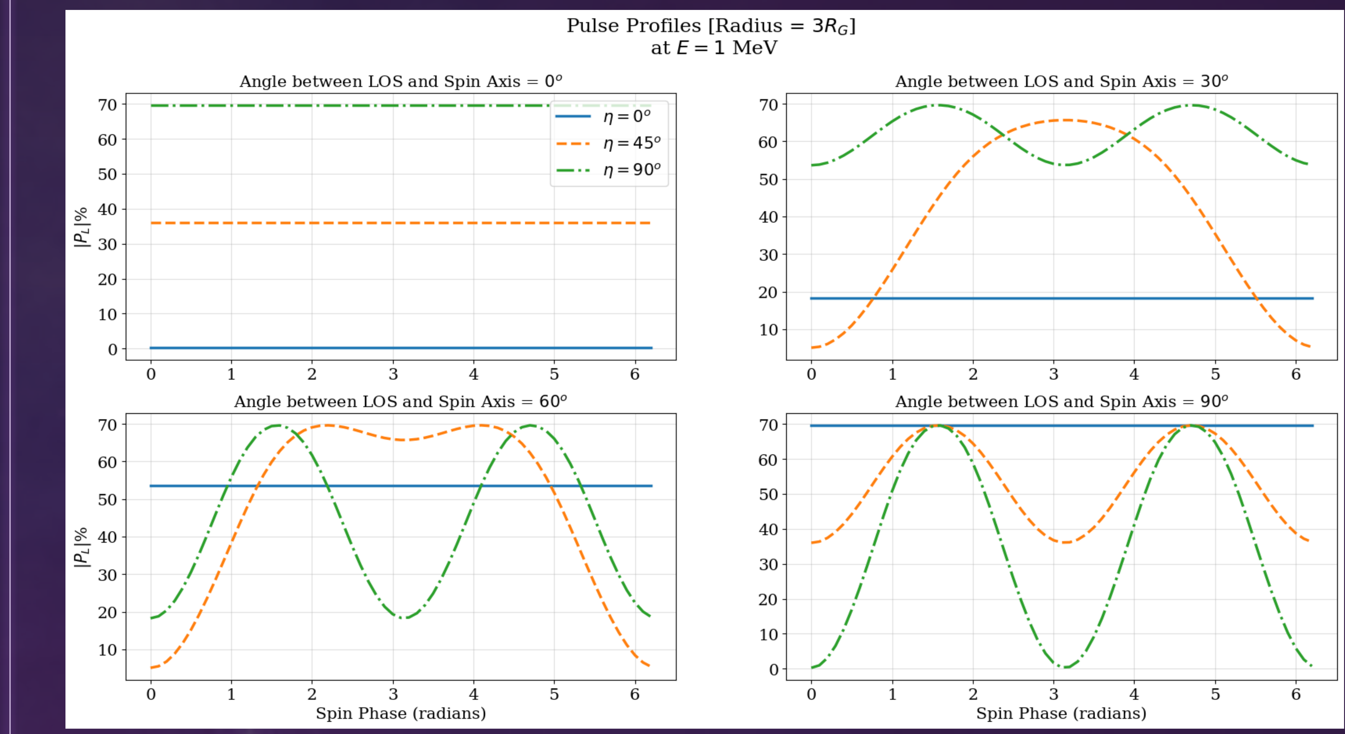
After an improvement, the errors in the approximation stay under 1% and we by-pass the need for ray-tracing.



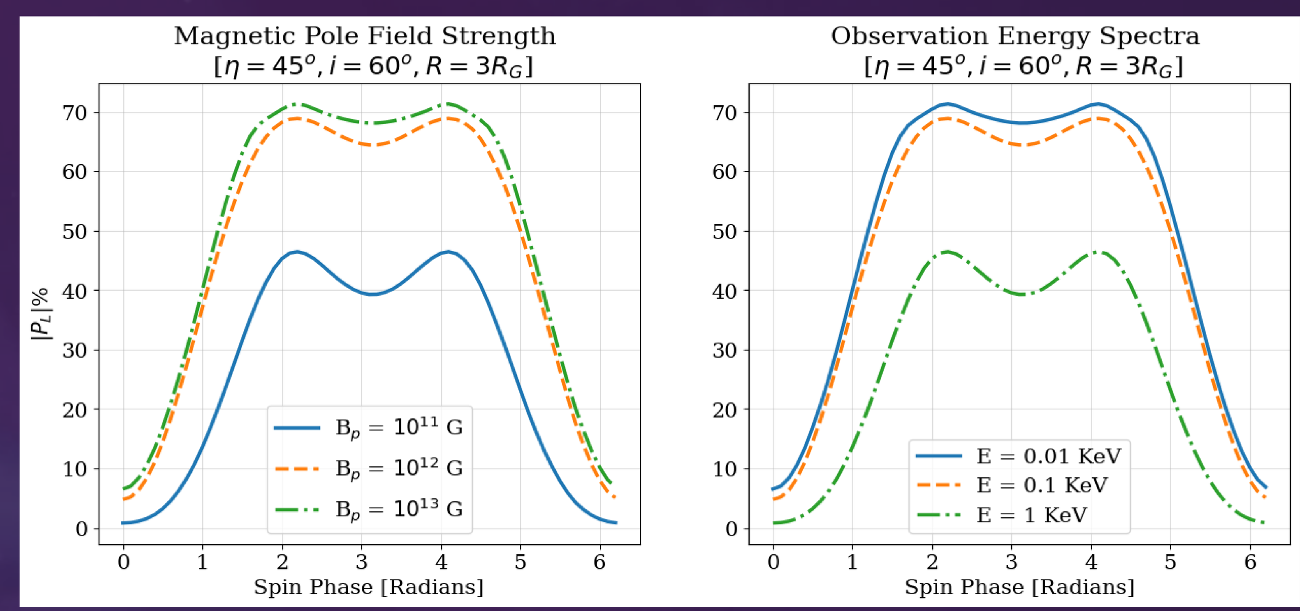
results

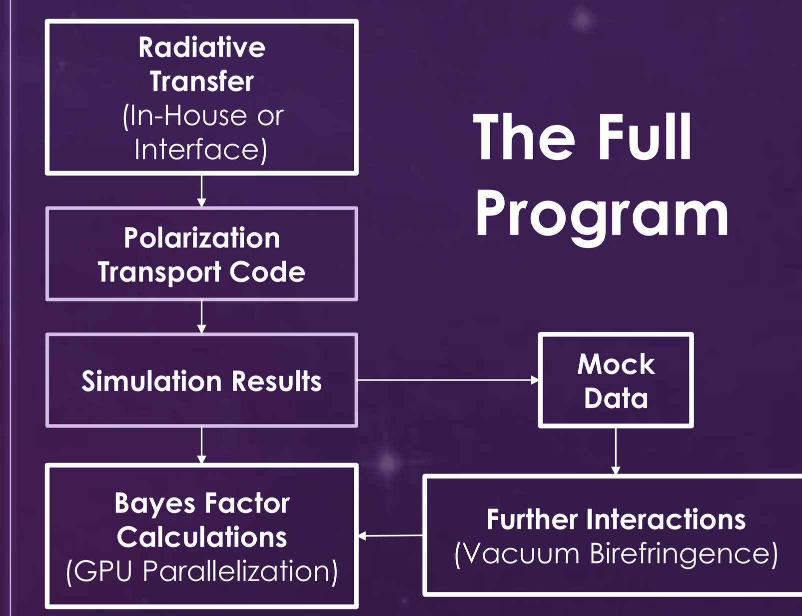
Simulations Results

On Y-axis, we plot the degree of linear polarization. As the star rotates, the projection of the surface changes along with observed varies polarization. Different lines represent different combinations of the NS geometry. Maximal linear polarization is observed when the magnetic and spin axis are offset by 90°. Constant polarization occurs when the spin axis becomes parallel to the line of sight.



Linear polarization increases with field strengths at magnetic poles. On observing the star in different photon energies, we get multiple pulse profiles for the same object (often displayed as 2D heatmaps in the literature on this subject). This gives additional data helpful in disambiguating between similar looking pulse profiles generated by different NS attributes.





Following are brief notes about potential trajectories that our work can take. Inclusion of Bayesian inference functionality (even with mock data) requires further parallelization on HPC infrastructure. More sophisticated radiative transfer models are required for better surface polarization maps. Finally, further interactions which affect polarization can also be modelled.

Background Image: Crab Nebula Pulsar as observed through Chandra X-Ray Space Telescope