Neutron Star Pulsars
and Polarization

Kartik Tiwari, Ashoka University

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I am Kartik and I am interested in computational astrophysics. I'll be talking about some aspects of my work on Neutron Star polarization.

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Neutron stars are interesting because they provide extreme conditions to test a variety of theoretical domains (such as GR, QED, CMT, High Energy Physics, etc).

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Studying polarization of the radiation coming from these neutron star pulsars provides a glance at the mechanisms producing the radiation. However, we do not observe neutron stars as the image on the left. We only see them as point sources with periodically varying total flux. Additionally, various mechanisms distort the nature of the radiation we receive.

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This is the question I am investigating – given some neutron star pulsar configuration, what polarization data should we expect from observations? And, given some data, what can we know about the neutron star?

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Neutron stars with different features dictate their pulse profiles. For example, consider a neutron star with two hot-spots (one primary and one secondary) on its magnetic poles. The angle between spin axis and magnetic axis and the angle between spin axis and line of sight produce different profiles shown on the right. The blue line on the top represents a case where the spin pole aligns with the magnetic pole and our line of sight is parallel to the spin axis. This is why we see a constant intensity. In the green line, we see the contribution from the primary pole and as it spins away from the line of sight, the contributions of the secondary pole come in. In the other two cases, we only see one hotspot throughout its spin phase evolution.

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Extracting information from the data about the neutron star attributes is a two step process. First, we need to understand how to model these pulse profiles and simulate their dependencies on physical parameters. Having understood the simulations aspects, we use Bayesian inference techniques, to narrow down the possible parameter space.

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Neutron stars are extremely compact objects. This means that geodesics bend considerably in their vicinities. Consequently, the parts which would be 'behind' a simple geometric projection start contributing in the total flux observed. This is demonstrated in the figure where I have simulated some trajectories in Schwarzschild spacetime. Additionally, the bending of the light rays also 'bends' the polarization observed. So, we need to account for these lensing effects. Unfortunately, explicitly raytracing photons from each discretized patch of the surface, for each spin phase would be extremely slow.

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But an approximation introduced by Belobordov connects the position of the ray on the Neutron Star surface with the bending angle required to reach the observer. In the figure, I have plotted exactly these quantities and we can see it is a very good approximation. In fact, with a further improvement I include, the errors remain under 1%. Using this, we bypass the need for ray-tracing explicitly.

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Recall the original question I wanted to investigate – Given a pulsar configuration, what polarization data to expect? My solution is this modular code I developed for polarization transport. I create a neutron star object by defining its attributes like magnetic pole strength, characteristic angles, etc. Then, there are parts of the code which provide the physics inputs. Currently, the code accounts for the lensing effects explained earlier, redshift and magnetic field variations across the surface. It then transfers the polarization to an observer at infinity and integrates over the entire visible surface to produce instantaneous flux. We then define a 'virtual observation' of the NS object by specifying what photon energy are we looking at and for how long. This generates the simulation results in the form of pulse profiles for specific stokes parameter. Another thing worth mentioning is that we can enumerate a catalogue of various NS objects with different properties and the 'virtual observations' can be launched in parallel.

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Here are some of the results generated using the code. On the Y-axis, we have the mod of the degree of linear polarization for the received radiation. As the star rotates, the projection of the surface changes and we see these pulsations. All these different lines represent different combinations of the NS geometry. Maximal linear polarization is observed when the magnetic pole is offset by the spin axis by 90 degrees. Constant polarization occurs when the spin axis becomes parallel to the line of sight.

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Here are some more dependencies I simulated. On the left, we notice the stronger magnetic field strengths lead to more polarization. We can also observe the star in different photon energies. So, we actually get many of these pulse profiles for the same object (often show as a 2D heatmap in the literature on this subject). This helps to disambiguate similar pulse profiles generated by different NS attributes.

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Finally, here are some topics I am stuying currently or would like to investigate in the future. One extension is to include a module for Bayesian inference. This is often very computationally intensive. I trying to perform the entire surface integration simultaneously. This is not possible on personal computers. I am in the process of translating the code to CUDA so it can sit on Ashoka's HPC infrastructure. For now I will be generating mock data by adding noise to my simulations and then testing how well I can extract original parameters from the inferences. Also, currently I assume simple polarization maps for the surface. But there are methods to generate better approximations for it. Some of them can be very complicated. So, I would like to either develop a radiative transfer code or implement a way to interface with an existing one.