The Effect of the Stellar Wind on X-ray Polarization in High Mass X-ray Binary Systems

Phiona Vall, Dr. Fabian Kislat Faculty Advisor
Department of Physics & Astronomy, University of New Hampshire, Durham, NH 03824

Introduction

- A high mass X-ray binary (HMXB) system is a compact object that is in a binary orbit with a high mass companion star, the compact object usually being a black hole or neutron star
- Observations of these systems allow us to study how matter behaves in the strongest gravitational and magnetic fields in the universe, these systems can be seen in Fig. 1. The compact star emits X-rays in the system, these X-rays are created from the mass accretion from the companion star , these X-rays are how we are able to study these systems. HMXB are also among the brightest systems in the sky, also making them easy to study.
- X-ray polarimetry is one tool we use to be able to study X-ray emitting systems. In 2022 two different experiments will be taking flight, those are IXPE [1] in space and XL-Calibur [2] on a balloon, both of these experiments will be able to give us a precise polarization measurement.
- Observations indicate that there is a dense stellar wind from the massive star in many of these systems. We want to know if polarization levels of photons change as they interact with the stellar wind once they leave the compact object . To do so, I have implemented a Monte Carlo ray tracing algorithm that tracks the photons and the polarization from the compact object to an observer.

Raytracing Algorithm

- We first begin to track each photon through the stellar wind, this is done by giving the photon a starting energy and direction.
- To locate the interaction point [3] of the photon we solve for x_2:

  $n_\lambda = \int_{x_1}^{x_2} \sigma \rho dx,$

  where σ and ρ are the interaction cross section and ρ the density, x_1 is the starting point of the photon, and n_λ is a randomly determined number of mean free paths. Irrespective of material properties n_λ follows a e^{-1} distribution. Once the number of mean free paths is determined we then use a Runge-Kutta integration method [4] to determine the exact location of the interaction point in the system. If the photon goes beyond specified radius , I used 100 times the radius of the star, it escapes, if it hits the star it is absorbed, otherwise it scatters.
- If the photon is scattered we simulate Compton scattering using the equation

  $\frac{\varepsilon'}{\varepsilon} = \frac{1}{1+\varepsilon(1-cos\theta)},$

  where ε and ε' being the energy before and after scattering ,respectfully. The angle of scattering is θ and the new velocity is picked at random isotropically. After the photon is scattered we then continue to track it and repeat the process.
- The polarization fraction is calculated with the use of Stokes parameters which are

  $$\begin{pmatrix} I \\ Q \\ U \end{pmatrix} = \begin{pmatrix} 1 \\ p\cos(2\varphi) \\ -p\sin(2\varphi) \end{pmatrix},$$

  they are one way to describe the polarization of light [5]. To calculate the Stokes parameters after the scattering process, we transform this vector using the Fano matrix [6,7]:

  $$T_{K-N} = \frac{1}{2} r_0^2 \left(\frac{\varepsilon'}{\varepsilon}\right)^2 \begin{pmatrix} 1+\cos^2\theta + (\varepsilon-\varepsilon')(1-\cos\theta) & \sin^2\theta & 0 \\ \sin^2\theta & 1+\cos^2\theta & 0 \\ 0 & 0 & 2\cos\theta \end{pmatrix}$$
- The chance of the photon scattering is given by a specific weight, the weight starts at 1 and is multiplied by its new weight after each time the photon is scattered the equation for the new weight is

  $\omega' = \frac{4\pi I'}{\sigma_{K-N}(\varepsilon)},$

  with ϵ being the energy before scattering , σ_{K-N} being the total cross section and I' is is the new Stokes parameter after multiplying it by the Fano matrix.

Tracking Photons In HMXBs

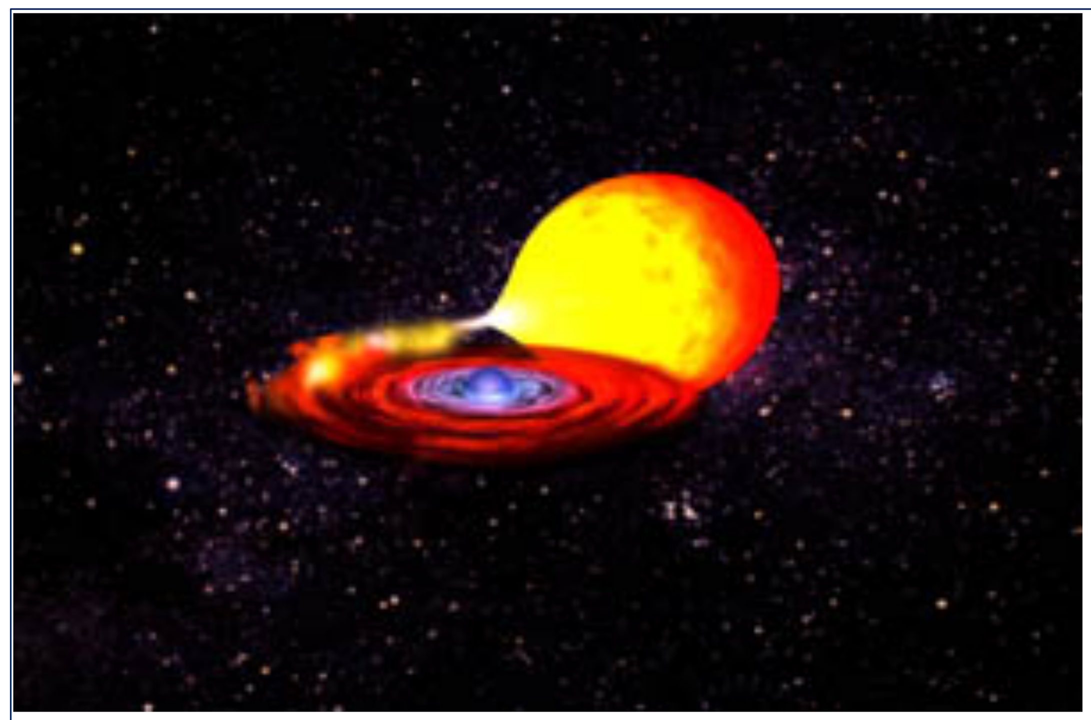

Figure 1. The image above shows a HMXB with a accretion disc surrounding the compact object in blue with the companion star in yellow fueling it. (Image Credit: NASA)

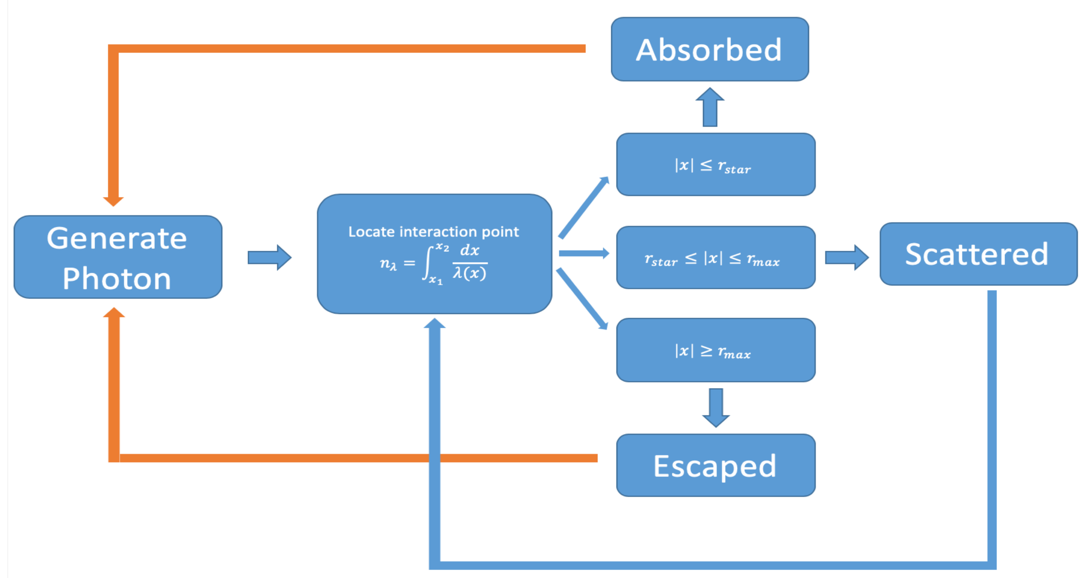

Figure 2: This is a flow chart showing how the photon is tracked, red lines mean the photon is deleted and the process is stared over and blue lines mean we are still working with the same photon.

Compton Scattering of Polarized Photons

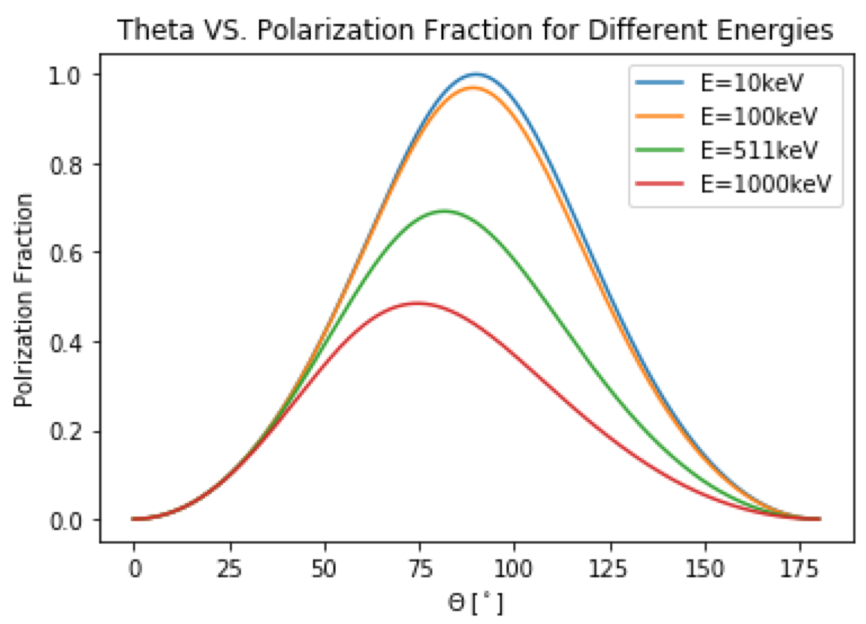

Figure 3: As we can see the lower the energy we start at the higher the polarization level will be, we see that the polarization fraction peaks when θ is close to 90 degrees.

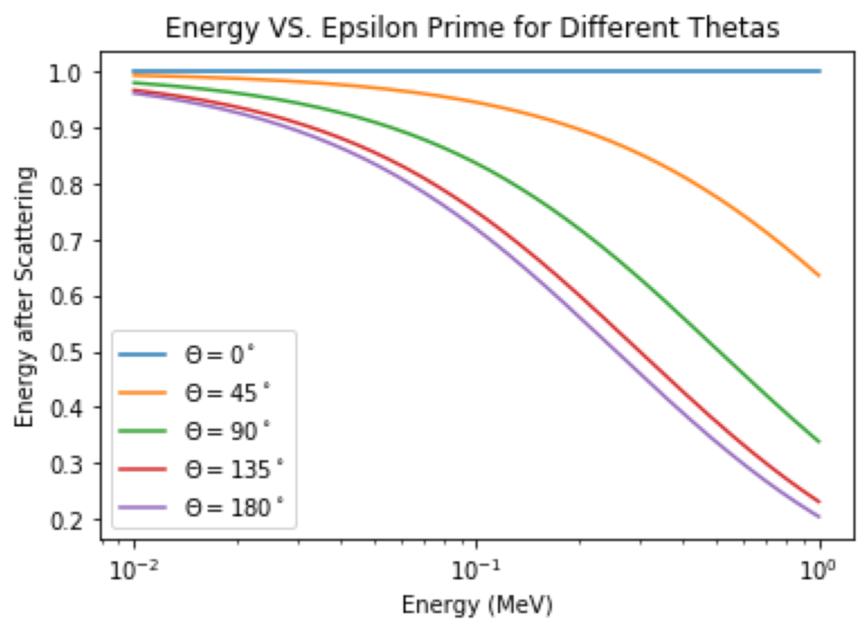

Figure 4: This graph illustrates the energy lost by photons with different scattering angles θ at a function of energy. As we can see a larger starting angle will decrease the energy after scattering as the energy before scattering increases.

Photon Scattering Weights

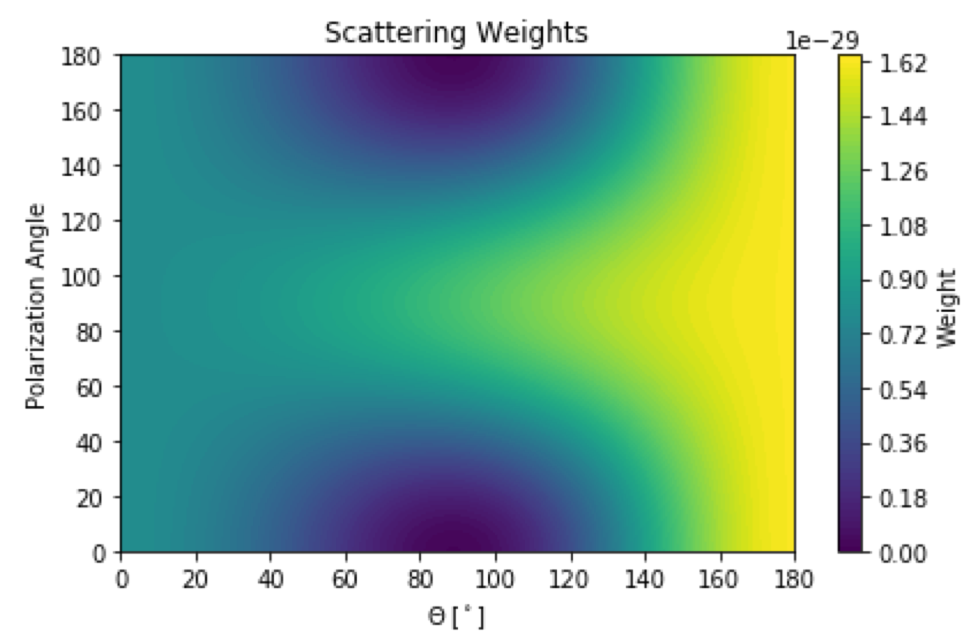

Figure 5: The weight assigned to photons as a function of scattering angle and azimuth relative to the polarization direction. This weight is proportional to the differential cross section. Backwards/forward asymmetry is reversed, which still needs to be investigated.

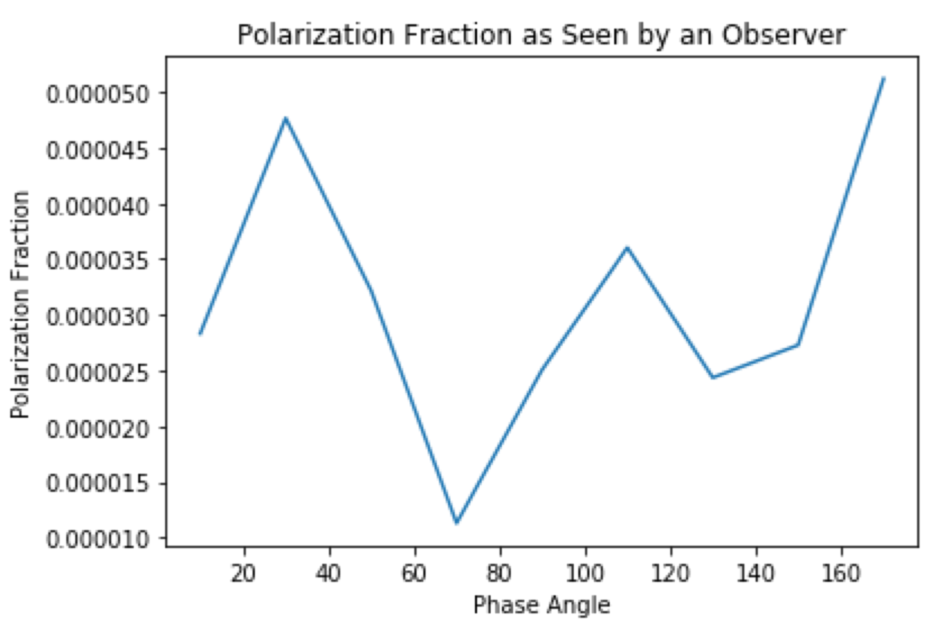

Figure 6: Polarization measured by an observer viewing the binary system edge on as a function of phase angle of the binary. Unlike Kallman et al. [8] we do not see any significant polarization.

Results

- As a diagnostic of the raytracing algorithm Fig. 5 shows the weight of polarized 100keV photons as a function of the scattering and azimuth angles.
- The parameters that were chosen for this system was for the compact object to emit unpolarized X-rays in a isotropic fashion, the stellar wind was spherical and symmetric with a density of

  $\rho(r) = \frac{M_{wind}}{4\pi r^2 v(r)}, v(r) = v_0 + (v_\infty - v_0)\left(1-\frac{r_*}{r}\right),$

  M_{wind} is the mass of the wind, r_* is the stars radius, r is the cut-off radius of the binary system, v_0 and v_∞ is the velocity of the wind and the terminal velocity, respectively.
- We simulated 10 million 10keV photons. We found that on average 0.017 % of photons scatter.
- Figure 6 shows observed polarization fraction as a function of phase angle of the binary system.

Conclusions

- We are hoping this beginning research will help future experiments to see how much they should expect polarization measurements to be alter by stellar wind.
- We were unable to reproduce the polarization reported by Kallman et al. [8]. The discrepancy still needs to be investigated before final conclusions can be drawn. One possible difference could be the stellar wind density.
- Further improvements to the method are planned. A current student at UNH is now taking the code that I have developed and added onto it to see what happens to the photons that may be scattered off the star. The project can also continue by changing the parameters of the system to be more realistic to the ones in a HMXB. My research was only the start to see how polarization levels are affected by the stellar wind

Acknowledgements

I would like to acknowledge my advisor for this project, Fabian Kislat, who showed me guidance throughout the entire project.

References

[1] Weisskopf M., et al. "The Imaging X-ray Polarimetry Explorer (IXPE)" Proc of SPIE Vol. 9905., doi: 10.1117/12.2235240

[2] Abarr, Q., et al. "XL-Calibur: Plans for a Next-Generation Hard X-ray Polarimeter" American Astronomical Society, Vol. 51, No.4

[3] Physics Reference Manual, 10.5 ed. Geant 4 Simulation Toolkit , 2019

[4] Press, William H., and William T. Vetterling. *Numerical Recipes*. Cambridge Univ. Press, 1997.

[5] Kislat, F., et al. "Analyzing the Data from X-Ray Polarimeters with Stokes Parameters." *Astroparticle Physics*, vol. 68, 2015, pp. 45–51., doi:10.1016/j.astropartphys.2015.02.007.

[6] Fano, U. "Description of States in Quantum Mechanics by Density Matrix and Operator Techniques." *Reviews of Modern Physics*, vol. 29, no. 1, 1957, pp. 74–93., doi:10.1103/revmodphys.29.74.

[7] McMaster W.H. "Matrix Reresentation of Polarization " Rev. Mod. Phys., 33 (1961) 8-27. doi:10.1103/RevModPhys.33.8.

[8] Kallman, T., et al. "X-Ray Polarization From High-Mass X-Ray Binaries." *The Astrophysical Journal*, vol. 815, no. 1, 2015, p. 53., doi:10.1088/0004-637x/815/1/53.