Smoothing of pulse periods caused by scattering of photons in cones of ultra luminous X-ray sources

Bachelorarbeit aus der Physik

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Contents

1 Abstract

The aim of these thesis is about the question, if scattering inside the cones of ultra luminous X-ray sources can lead to the observed sinusoidal pulse profile of some ULX. At the moment we already know something about these sources. For example we can explain the luminosity of these sources which exceeds the Eddington luminosity by a few times with scattering inside these cones, which lead to a so called beaming. Fürst et al. (2016) showed that there are some ultra luminous X-ray sources which harbor a neutron star in their center and this sort of ULX show a sinusoidal pulse profile, even when we expect a strong collimated pulse profile.

In this thesis I calculated the possible time delay caused by the scattering inside these cones for given heights of the cone. Furthermore I also checked if the open angle or the inclination of the observer influences the pulse profile.

In the end I folded the probability with a sharp Gaussian pulse profile and showed that the scattering can lead to a sinusoidal pulse profile.

2 Zusammenfassung

Das Ziel dieser Arbeit ist es, die Frage zu beantworten ob die Streuung von Photonen im Inneren von "ultra luminous X-ray sources", auch kurz ULX, zu den beobachteten sinusfrörmigen Pulsprofile einiger ULX führen kann oder nicht. ULX sind bis heute immer noch nicht genau verstanden. Dauser et al. (2017) zeigte, das die Streuung der Photonen im Inneren des kegelförmigen Materieflusses, die beobachteten Leuchtkräfte erklären kann.Fürst et al. (2016) zeigte zu dem dass es ULX gibt, die als zentrales kompaktes Objekt einen Neutronen Stern beherbergen und ein sinusförmiges Pulsprofile haben. Für solche Objekte erwartet man jedoch aufgrund der starken Leuchtkraft ein viel schärferes Pulseprofile als das beobachtete Pulsprofile.
In dieser Bachelorarbeit habe ich die Zeitverschiebung berechnet, die durch die einzellnen Streuungen entsteht. Ich habe zu dem weiter untersucht ob der Öffnungswinkel oder die Inklination des Beobachters Auswirkungen auf die Zeitverschiebung hat.
Zum Schluss dieser Arbeit habe ich die berechnete Wahrscheinlichkeit mit einem scharfen gaussförmigen Profil gefaltet und gezeigt das die Faltung zu einem sinusförmigen Pulsprofil führen kann.

3 Introduction

Since thousands of years, the mankind explores the night sky. Before the invention of Global Positioning System, knowledge in astronomy was necessary to navigate ships across the oceans. Apart from that ancient cultures like Egyptian, Persian or Greeks participate astronomy, to understand their role in the universe. The key step for modern astronomy in Europe was the invention of the telescope in the Netherlands at the beginning of the 17th century and therewith the discoveries of the four Jupiter moons Io,Europa,Ganymed and Kallisto by Galileo Galilei.
The conclusion, that the sun and not the earth is the center of the solar system is the main acquisition of the 16th century. These days modern technology like satellites such as the XMM Newton telescope and observatories, like the paranal observatory, allow a more detailed view of the night sky, but astronomy still stands in the footprints of Galileo Galilei, Johannes Kepler and Edwin Hubble.
Nowadays astronomy is divided in different subtopics. One of these subtopics is X-ray astronomy beside radio-astronomy etc.. X-ray astronomy is compared to optical astronomy a young subtopic and became possible with the development of satellites and rockets in the second half of the 20th century.
Because of the absorption of X-ray radiation by the atmosphere of the earth (figure 1), X-ray astronomy depends on satellite and rocket technology. For X-ray astronomers the objects of interest are black holes, neutron stars, AGNs (Active Galactic Nuclei) and galaxy clusters.

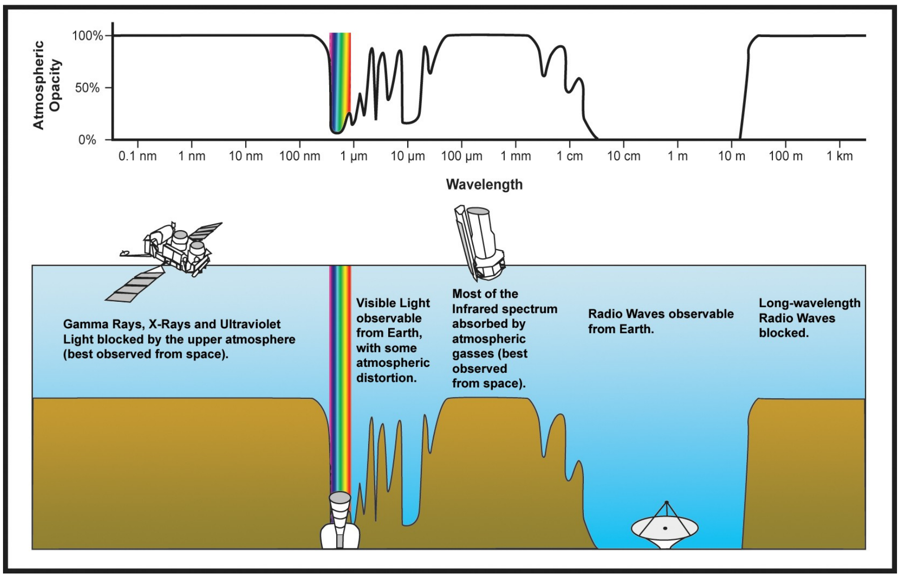

Figure 1: Electromagnetic spectrum and the absorption of the atmosphere of the earth for that. Furthermore possible observation methods for the given energy range (Quelle: `http://gsp.humboldt.edu/olm_2015/Courses/GSP_216_Online/lesson2-1/atmosphere.html`)

4 Motivation

Figure 2 shows the sky in the energy range between 3keV and 20keV, and is therefore not in the energy range, where the human eye is sensitive. Although we know already much about astronomy, this part of the electromagnetic spectrum shows actions which are still unknown to the mankind. Accretion around compact objects and strong magnetic fields caused by neutron stars and the hot gas in the center of galaxy clusters emit radiation in the X-ray range. This phenomena help to understand the fundamental relations of physics. To prove theoretical theses in particle and gravitational physics, X-ray astronomy is necessary and because of the high energies needed, the only possible way to prove this theses.

Apart from that we still do not know everything in X-ray astronomy and many things can not be explained with simple default models. Ultra luminous X-ray sources for example beside many other, are one of these X-ray emitting objects, where our current knowledge about astronomy is not sufficient enough (King, 2008). To explain Ultra luminous X-ray sources we have to find out how these sources produce radiation. These models include for example scattering of photons inside the cone and the effects of the scattering on light curves and pulse profiles.

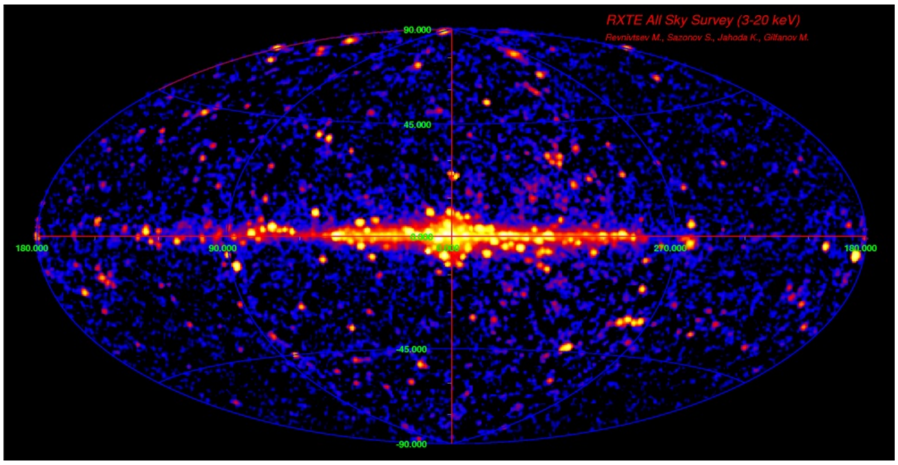

Figure 2: RXTE All-sky-Survey in the energy range between 3keV and 20keV. Shows galactic and extra galactic sources, which emits x-rays.
(Quelle: `http://astro.uni-tuebingen.de/seminars/scripts/ankuendigung/highenergysources.shtml`)

5 Compact objects

At this point it is useful to make a brief insertion of the so called compact objects. After a massive Star became a so called red supergiant with a mass of about 50 $M_\odot$(Maeder, 1981), the star begins to collapse and ends in a supernova. For this kind of star the compact object is black hole (Shapiro & Teukolsky, 1986). The supernova can reach

luminosities, which exceed the luminosities of its host galaxy (Carroll & Ostlie, 1996). Is the mass of the star between $10M_\odot$and $20M_\odot$the compact object after the supernoa is a neutron star (Carroll & Ostlie, 1996). Figure 4, the right branch shows the evolution of a high mass star, which ends in a black hole or a neutron star. Apart from that it is also possible, that a sun like star can end as neutron star or a black hole, when it is gravitational bounded in a double star system.
After a sun like star became a so called red giant and pushed off his atmosphere it ends in a so called white dwarf (figure 4 left branch), therefore the mass of the sun like star has to be below the Chandrasekhar-limit (Carroll & Ostlie, 1996).The Chandrasekhar-limit is the upper limit of the mass of a white dwarf. Only if the mass of the star lies below the Chandrasekhar-limit the white dwarf can become stable.(Carroll & Ostlie, 1996)
The white dwarf is then surrounded by a planetary nebula (Shapiro & Teukolsky, 1986). But in some cases this does not mean the end of the evolution of a sun like star. If the sun like star has a companion star, therefore the sun like star is a part of a double star system, the white dwarf starts accreting material from its companion (Shapiro & Teukolsky, 1986). This takes place until the white dwarf exceeds its Chandrasekhar-limit. Then the white dwarf starts to collapse, which lead to supernova typ Ia (Carroll & Ostlie, 1996). After the supernova typ Ia the white dwarf became a neutron star (Carroll & Ostlie, 1996).

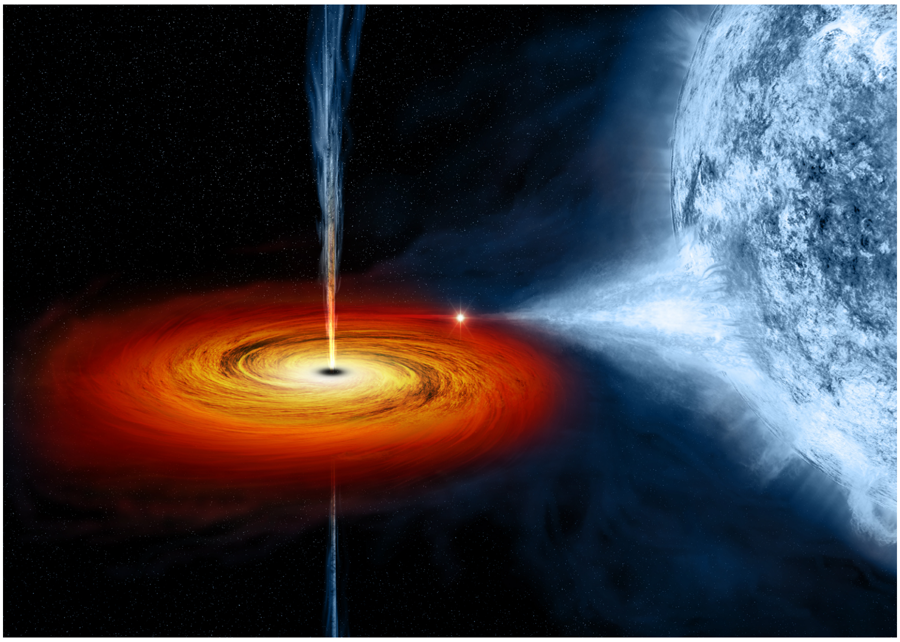

Figure 3: Artist impression of an accreting compact object (left) and the donor star (right)
(Quelle: `https://www.nasa.gov/audience/forstudents/k-4/stories/nasa-knows/what-is-a-black-hole-k4.html`)

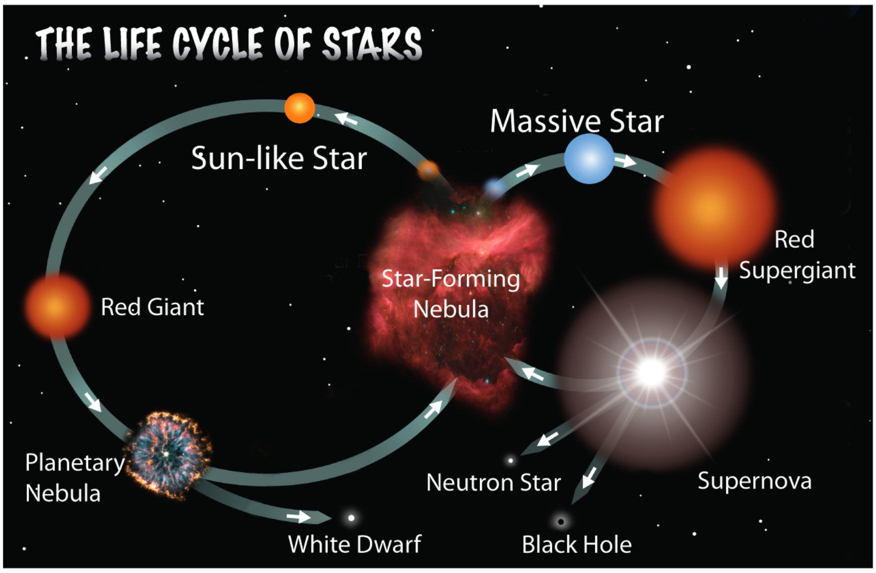

Figure 4: Artist impression of the development of a star depending on the size of the star
(Quelle: `http://s4.thingpic.com/images/pY/WPUXrxoxzADNtfn6QNpghixi.png`)

5.1 Black holes

Now there I already mentioned black holes it is time to explain black holes.
There are three kinds of so called black holes, supernova remnant black holes with an average mass of about $10M_\odot$(Coleman Miller & Colbert), intermediate mass black holes with a mass between $10^2 - 10^4 M_\odot$(Coleman Miller & Colbert) and supermassive black holes in the center of galaxies with a masses of a $10^6 - 10^8 M_\odot$(Ghez et al., 2008). All of them have one thing in common, that they bend the space-time so strong, that not even light can escape from them and gets trapped inside these objects. Beside black holes, a massive star can also end as a neutron star.

5.2 Neutron stars

Beside black holes, massive star can also become a neutron star during their evolution. A neutron star is the third compact object beside black holes and white dwarfs. Neutron stars are compact objects with strong magnetic fields up to 10^{13} Gauss (Lattimer & Prakash, 2004). The average mass of a neutron star lies between $1.2M_\odot$and $2.0M_\odot$. Neutron stars have a radius of about 12km (Lattimer & Prakash, 2004). These objects are formed by the gravitational collapse of a massive star with a mass of about $>8M_\odot$(Lattimer & Prakash, 2004).
To observe black holes and neutron stars, these systems have to accret material from

a companion star (stellar mass black holes and neutron stars) and build an accretion disk around itself or just build an accretion disk around them without accretion from its companion (supermassive black holes). Thereby they become visible in the X-ray spectrum and can be observed by X-ray satellites like XMM-Newton or Chandra.

5.3 Low mass X-ray binaries

For low mass X-ray binaries the companion compact object (neutron star, black hole or white dwarf) accrets material over the lagrange point. The companion star fills its Roche lob and thereby the compact object builds an accretion disk around itself (Verbunt & van den Heuvel). Figure 5 shows an artist impression of a low mass X-ray binary system, where the compact object accrets over the lagrange point.

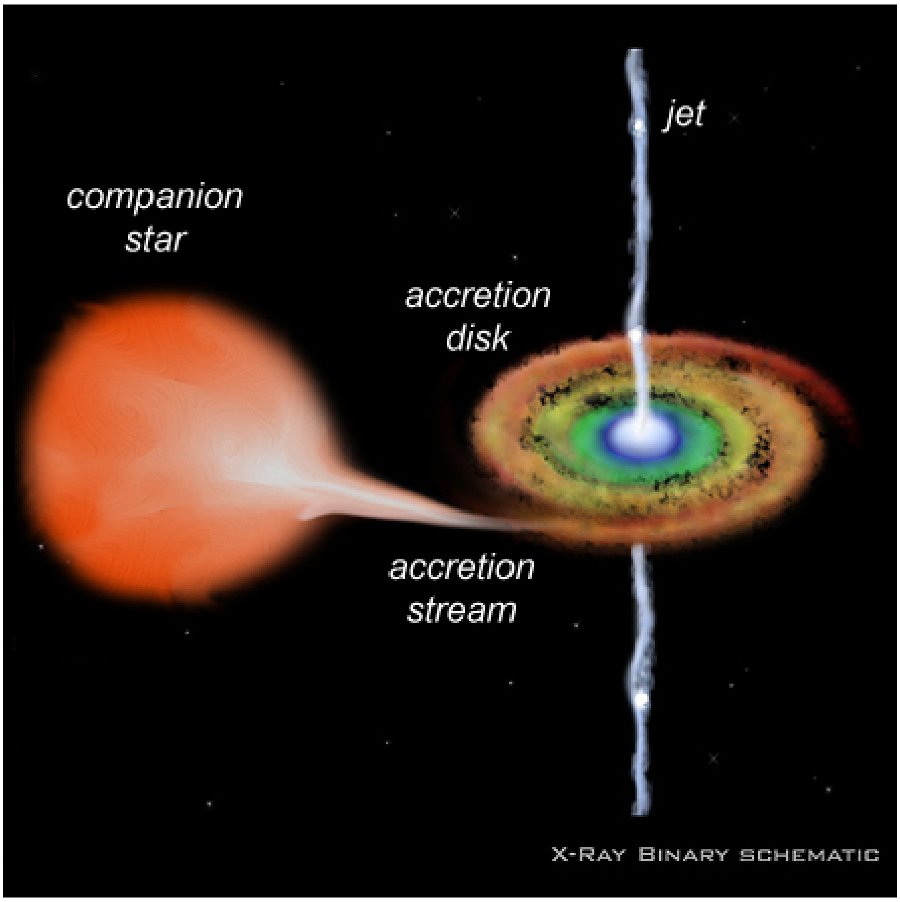

Figure 5: Artist impression of a low mass X-ray binary
(Quelle: http://www.cefns.nau.edu/geology/naml/Meteorite/Images/X-ray_Binary.jpg)

5.4 High mass X-ray binaries

Compared to low mass X-ray binaries where the accretion of material over the lagrange point dominates, for high mass X-ray binaries the accretion of the compact object can be separeted in to different accretion phenomena. The accretion over the lagrange point like for Low mass X-ray binaries and accretion from the stellar wind (Verbunt & van den Heuvel). The companion star is a so high mass star, that it loses parts of his atmosphere, which get blown out in the interstellar medium. Additional to the accretion from the stellar wind, the accretion over the lagrange point still takes place. The luminosity of the compact object therefore is highly variable because of the inaccurate mass accretion from the stellar wind (Verbunt & van den Heuvel). Figure 3 shows an artist impression of a high mass X-ray binary system which also accrets over the lagrange point like a low mass X-ray binary.

6 Ultra Luminous X-ray Sources (ULX)

Now we already know something about black holes and neutron stars it is time to explain ULXs. ULXs are low mass X-ray binaries or high mass x-ray binaries with an extremely high accretion rate. Hence ULXs can exceed X-ray luminosities of 1×10^{39}ergs^{-1} (Dauser et al., 2017) or they harbor a so called intermediate mass black hole in the center and therefore they do not exceed their Eddington luminosity.
The luminosites of ULXs lay between the luminosites of stellar mass black holes and active galactic nuclei (AGNs) Stobbart et al. (2006).
These sources are significant separated from the center of there host galaxy they can not be supermassive black holes Fürst et al. (2017). Because of their high luminosity, some have been speculated that this sources are intermediate mass black holes Fürst et al. (2017).
But there are at the moment three known sources which harbor a neutron star in the center NGC 7793 P13 (Fürst et al., 2016), M82 X-2 (Bachetti et al., 2014) and NGC 5907 (Fürst et al., 2017). NGC 5907 has a peak luminosity of about 10^{41} ergs^{-1} (Fürst et al., 2017). Apart from that NGC 5907 accretes with about 500 times the Eddington rate (Israel et al., 2017) compared to an X-ray luminosity of 2×10^{40}ergs^{-1} of M82 X-2 and therefore with a peak luminosity of more than 100 times the Eddington luminosity (Fürst et al., 2016). NGC 7793 P13 can reach a peak luminosity of about 10^{40}ergs^{-1} (Fürst et al., 2016). All three sources therefore exceed the Eddington limit for a neutron star with a mass of about $1.4M\odot$(Fürst et al., 2016) by a few times.
For the spectrum of ULXs we expect power-law hard X-ray spectrum, with a roll-over at energies of about 100 keV Fürst et al. (2017). In the reality we see a different spectral shape. The spectrum of ULXs seems to be thermal in origin with a fast turn-over above 10keV (Fürst et al., 2017). The spectrum therefore shows that the majority of ULXs are stellar remnants accreting above the Eddington rate (Fürst et al., 2017).
Due to the high mass accretion from the donor star, two cones of fully ionized plasma are formed, each at one pole of the compact object (figure 3) (Fürst et al., 2016). The physic inside these cones is still not complete clear, but apart from that some theories show that maybe some interesting effects take place. One of them is the so called scattering of photons inside these cones (Dauser et al., 2017). The scattering of photons inside the

cones can be used to explain the high luminosity of ultra luminous X-ray sources which exceed the Eddington luminosity by a few times. The Eddington luminosity therefore is the maximum luminosity caused by accretion. Because of their high luminosities and because of their lack of pulsation, it is thought, that the majority of ultra luminous X-ray sources harbor black holes in their center and not neutron stars.Fürst et al. (2016). Apart from that it is necessary to mention, that at the moment there is no model which can explain the observed characteristics of these three ultra luminous X-ray sources (Fürst et al., 2016).

6.1 Scattering

All simulations of the scattering are done with code from Dauser et al. (2017), I only added some functions to calculate the time delay, which will be explained later in the text.

One explanation for the observed luminosities of the three objects is that the emitted photons get trapped inside the fully ionized cone Dauser et al. (2017) and gets geometrically beamed out. King (2009) confirms the global geometry of the outflow region to be conical. The scattering inside the cone is modelled by the Klein-Nishina formula (equation 1), where E' is the energy of the scattered photon, E is the originally energy of the photon, $\alpha = \frac{1}{137}$ the fine structure constant and Φ is the angle under which the photon gets scattered. The scattering depends on the open angle $2\times\Theta$ of the cone between the surface and the rotation axis of the outflow, the height of the emitting area h_{emit} above the compact object, the height of the cone itself h_{max} and the inclination angle i for a given observer. A sketch shown in Figure 6 visualises the given parameters. For the scattering process Dauser et al. (2017) assume that only electron scattering takes place at the surface of the cone.

Another important parameter, which influences the amount of scatterings inside the cone, is the velocity of the outflow. The out flowing winds of ultra luminous X-ray sources are modeled with magnetohydrodynamical (MHD) studies and are way to complex for this work. Therefore Dauser et al. (2017) suppose a fully ionized plasma inside the cone and a constant outflow and velocities in the range of $v \geq 0.2c$ (Middleton et al., 2015)

Beside the magnetohydrodynamical studies Dauser et al. (2017) also ignores clumpy clouds inside the outflow, because the calculations for this are also way to complex.

General relativistic effects are also secondary, according to Dauser et al. (2017), to the scattering processes and so Dauser et al. (2017) describes the path of the photons between their interactions with the cone with straight, Euclidean,trajectories.

Dauser et al. (2017) showed, that for an open angle of ten degree, a emitted photon will be scattered around 50 times inside the cone. For an open angle of about 20 degrees, a emitted photon will be scattered up to 15 times.

The code was written by Dauser et al. (2017) and is done by a Monte Carlo simulations in three dimensions.

$$\frac{d\sigma}{d\Omega} = \frac{1}{2} \cdot \frac{\alpha^2}{m^2} \cdot \frac{(E')^2}{E^2} \cdot \left(\frac{E'}{E} + \frac{E}{E'} - sin^2(\Phi) \right) \quad (1)$$

$$\frac{E'}{E} = \frac{1}{1 + \frac{E}{m} \cdot (1 + cos(\Phi))} \quad (2)$$

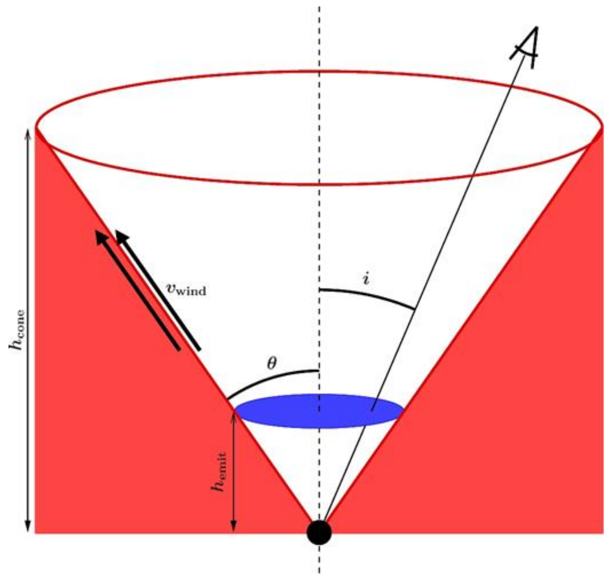

Figure 6: Sketch of the cone of an ultra luminous X-ray source with the parameters h_{max},h_{emit}, tht inclination of the observer i and half open angle Θ, taken form Dauser et al. (2017)

6.2 Smoothing of pulse profile

Another important and also interesting aspect beside the scattering of photons inside the cones of some ultra luminous x-ray sources is the fact, that only three known ultra luminous x-ray sources show a pulse profile and harbor therefore neutron stars in the center (Fürst et al., 2016). With an magnetic filed strength of 1.5 $\times 10^{12}$ G, NGC 7793 P13 is one of this sources with a coherent pulsation period of 418ms and a observed peak luminosity of 10^{40}ergs^{-1} (Fürst et al., 2016). Another example for an ultra luminous X-ray sources which harbors a neutron star is NGC 5907 ULX 1 (Fürst et al., 2017).
Or M82 X-2 which also harbors a neutron star in the center(Bachetti et al., 2014). Because of the high luminosity of NGC 7793 P13, a wind-fed system (high mass X-ray binary) is unlikely due to the small mass accretion for such a system and it is therefore more likely a low mass X-ray binary, where the companion star is filling its Roche lobe (Fürst et al., 2016).
With a luminosity of around 10^{40}ergs^{-1} it is most likely that outflow is strong collimated, which is in contrast to the observed smooth sinusoidal pulse profile (figure 7) (Fürst et al., 2016). One possible reason for the observed smoothed pulse profile could be, that the

source emitts photons in sharp delta peaks and that the smoothing of the pulse profile is caused by the scattering of photons inside the cones.
The photons get emitted at a height h_{emit} above the compact object. After that it travels on straight eucledian trajectories through the cone. On its way, the photon gets scattered inside the cone, which is described by the Klein-Nishina formula (equation 1). Due to the scatterings inside the fully ionized cone, the photon leav the cone with a time delay Δt. It is clear that not all photons get scattered inside the cone, there are some photons which leave the cone without any scattering. Nevertheless the majority of the photons get scattered inside the cone. The observed pulse profile therefore is a combination of the scattered photons with the time delay Δt and the photons which did not get scatttered. This combination can lead to the smoothed pulse profile of the three ultra luminous X-ray sources which harbor a neutron star in their center.
This effect, the smoothing of pulse profiles due to scattering inside the cones, will be the main topic of this bachelor theses.

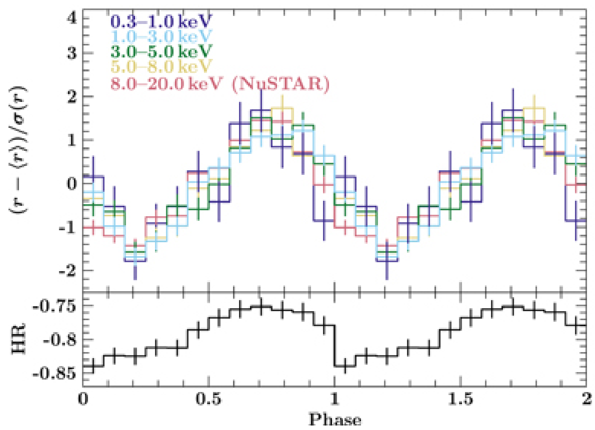

Figure 7: Energy resolved pulse-profile taken with XMM-Newton in the energy ranges 0.3-1.0,1.0-3.0,3.0-5.0,5.0-8.0keV and the 8-20kev taken with the NuSTAR satellite taken form Fürst et al. (2016)

7 Simulations

For the simulations of the smoothing of pulse profiles I used the code from Dauser et al. (2017). As starting parameters an open angle of ten degrees, an inclination of 10 degrees and one million photons were chosen for the simulations.
After the photon got scattered multiple times inside the cone it leave the cone under a certain inclination. The complete trajectory of the photon is the sum of the trajectories

between the scatterings in three dimensions. I also only counted the photons which did not fall into the compact object and which got ejected under a certain inclination i±1. Figure 8 shows the calculated time delay caused by the scattering for different heights h_{max} of the cone. It is easy to see, that with an increasing h_{max}, the photons have to travel a longer distance inside the cones until they get ejected and therefore they have a larger time delay than photons with a shorter way.
To get an overview of amount of photons, which get ejected at each hight, I plotted the time delay of the photons over the probability figure 9. Apart from that I also fitted Gaussian functions on the time delay functions to get an overview of the characteristic parameters for each curve. The resulting parameters are also plotted for different h_{max}, to show if there is any depends between the hight of the cone and the parameters.
For the simulations the ISIS-version 1.6.2-37 was used.

7.1 Time delay

Because of the fact, that we want to explain the observed sinusoidal pulse profile of some ultra luminous X-ray sources, I assumed a neutron star with a mass of 1.4 solar mass for the calculations. For a neutron star 1.4 solar masses is the typical average mass. A galactic black hole or an intermediate mass black hole would not allow a pulse profile at all and are therefore not expected to be hosted in this kind of ultra luminous X-ray source. Because of the pulse profile (figure 7) we expect a neutron star with a strong magnetic field hosted inside of these sort of ULXs (Fürst et al., 2016). Black holes do not allow pulse profiles and are therefore not possible.
The time delay is defined as the time Δt, from the point where the photon gets emitted until to the point where it leav the cone.
For the simulations of the time delay I calculated the intersection of the photon trajectory and the cone. The photon trajectory therefore only increases on the basis of scatterings inside the cone, which depends on the open angle of the cone. To get a better statistic I simulated all runs with one million photons, where the majority got scattered inside the cone.
For the simulations I chose different heights h_{max} 100rg, 1000rg, 10000rg and 100000rg to get an overview of how big the time delay can be and how it depends on height of the cone, which is important under the aspect of the smoothed pulse profile.
I also checked if there is a connection between the inclination of the observer and the maximum time delay of the photons (figure 10). The maximum time delay is for each curve is almost the same and only the amount of photons changes. Therefore there is no connection between the maximum time delay and the inclination of the observer. Figure 10 shows that only the curve for an inclination of about 0 deg is different to the other. For this parameter configuration the majority of the photon get ejected with almost no time delay compared to the other parameter configurations where the majority of the photons has a time delay of about 0.005 seconds. For this plot I choose as starting parameters an open angle of ten degrees, a height $h_{max} = 1000$rg and for a better statistic one million photons.

Apart from that I also checked if there is a correlation between the open angle and the maximum time delay. Figure 11 shows that the maximum time delay does not depend on the open angle of the cone. Because of this I only concentrated my work on the correlation between the height h_{max} of the cone and the time delay.
The time delay of the photons strongly depends on the height of the cone (figure 8). For a hight of 100rg we can get a time delay up to 0.001 second. Compared to a time delay of almost one second for an cone hight of 100000rg (figure 8), where rg means gravitive radi.
Figure 9 shows the probability of a photon to get ejected with a certain time delay under an inclination of ten degrees and an open angle of also ten degrees. The maximum of the probability is at four percent for this configuration of parameters. It is clear to see, that the probability for a photon to get ejected under the given parameters does not depend on the height of the cone h_{max} figure 9.

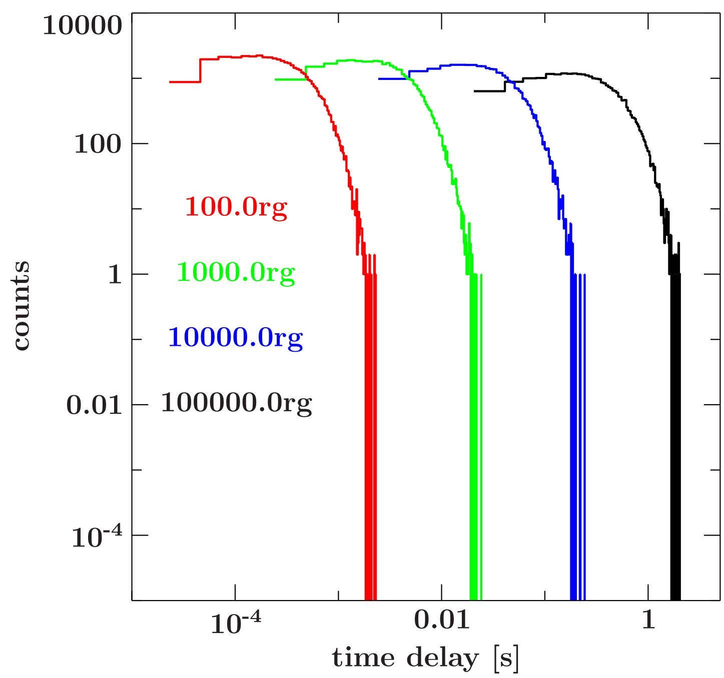

Figure 8: Number of photons n=1000000,open angle 10deg, an inclination of 10deg and a changing h_{max}

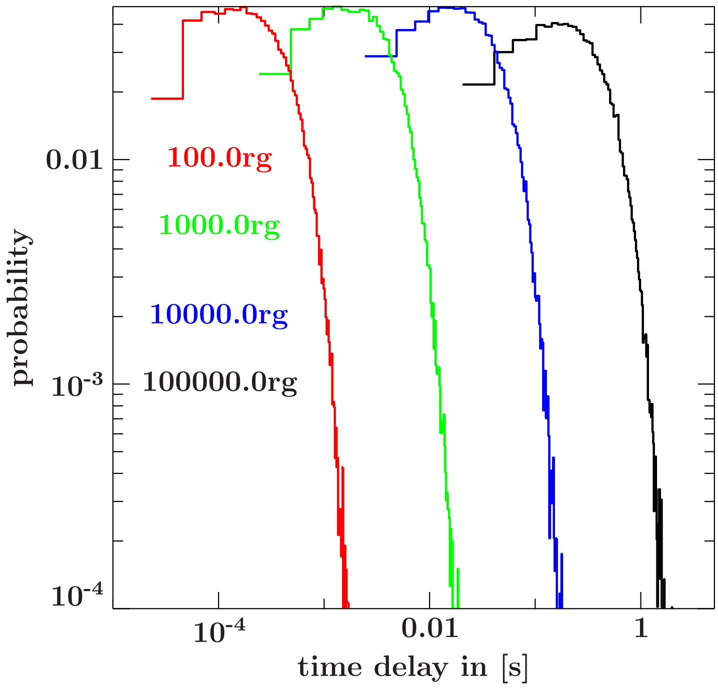

Figure 9: Probability of a photon to get detected for an inclination of 10 deg, an open angle of 10 deg and a changing h_{max}

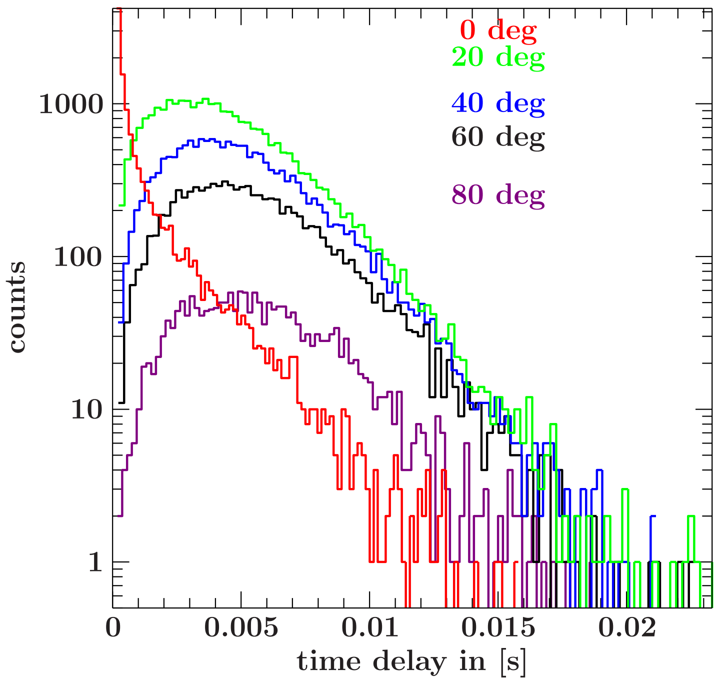

Figure 10: time delay for different observer inclinations with an open angle of 10 degrees, a hight h_{max} of 1000rg and one million photons. Shows apart from the counts no difference, for the maximal time delay, for the inclinations

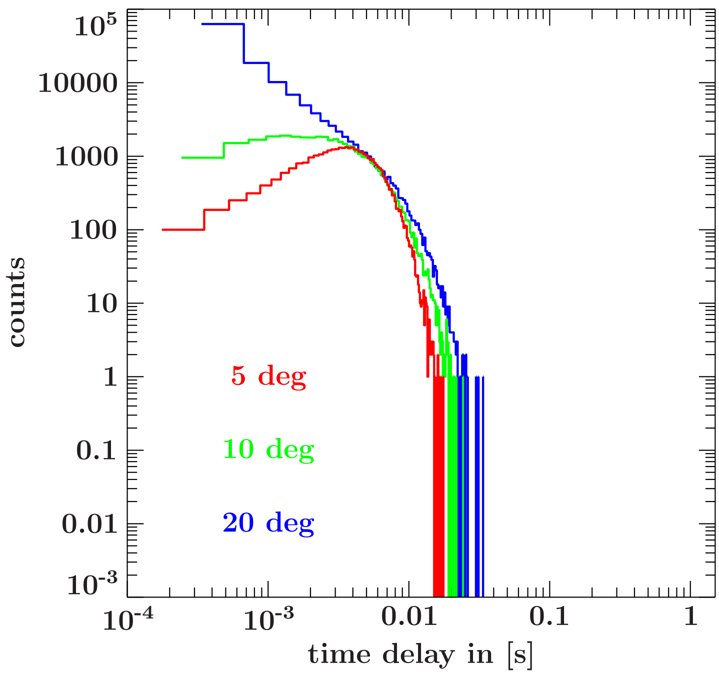

Figure 11: change of the open angle for h_{max} = 1000rg and an inclination of 10 deg.

7.2 Gauss function fits

After the simulations I had a rough idea of how much time delay we can generate by changing the hight the of the cone of the ultra luminous X-ray source. To get more detailed informations about the curves, I used the ISIS function *array fit gauss*, which fits a Gaussian function on our data curve. The function calculates the parameters center, sigma, area and χ^2 of the fitted Gaussian function.
Figure 12 shows, that the center of the Gaussian function increases linear with increasing height of the cone h_{max}. The same behavior shows figure 13, where the σ increases with an increasing h_{max}. On the other hand, tabular 2 shows, that the area of the Gaussian function decreases with an increasing height of the cone. Tabular 2 shows also an almost constant χ^2 for a changing h_{max}. With an average χ^2 of about 9.19, tabular 2 shows, that the Gaussian function does not describe the curve of the time delay very well, a χ^2 around 1 would be the fact if the model describes the data very well. Especially for the first fit (figure 16) with an χ^2 of 17.9359, the Gaussian fit model does not describe the reality. It is clear we need a more complex function to describe the time delay histogram. But for an overview of how the time delay depends on the parameters, a Gaussian fit is good enough. Even when the Gaussian function does not describe the time delay curves, the fit-parameters show the expected behavior for the time delay. The center increase with an increasing h_{max}. The same is for the σ where the fit-parameters describe the expected behavior. In tabular 1 and tabular 2 all fit parameters are listed, each for the best possible fit of the Gaussian function (figure 16 - figure 22).

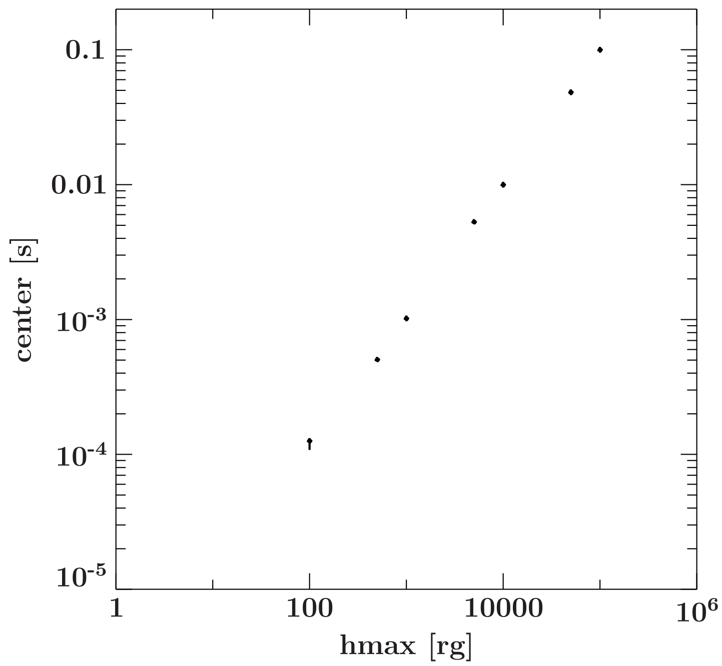

Figure 12: center of the fitted gauss for different h_{max} of the cone

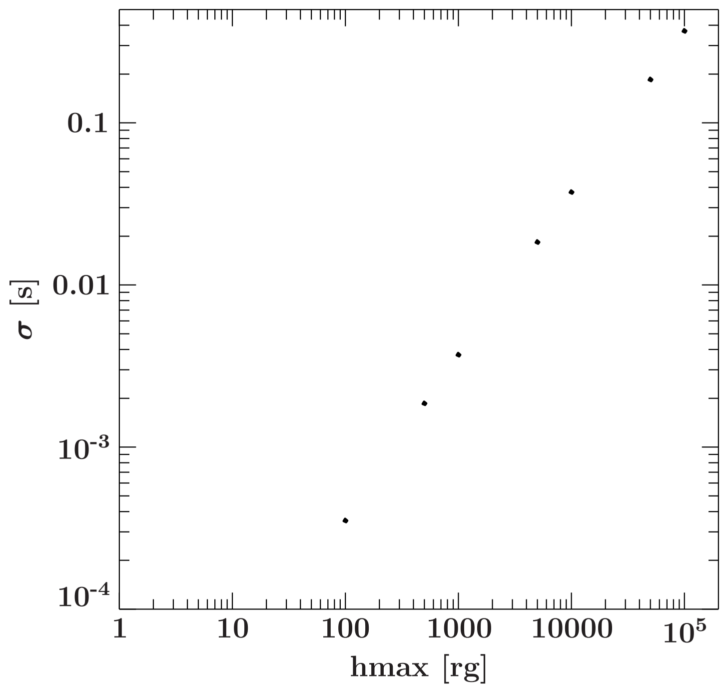

Figure 13: σ of the fitted gauss for different h_{max} of the cone

h_{max}	center[s]	sigma[s]	area
100.0rg	$0.000126^{0.000006}_{0.000018}$	$(3.518^{0.037}_{0.029}) \times 10^{-4}$	$(7.08674^{0.00004}_{0.00197}) \times 10^{4}$
500.0rg	$0.000504^{0.000020}_{0.000021}$	$(1.860^{0.017}_{0.017}) \times 10^{-3}$	$(6.7398^{0.0010}_{0.0010}) \times 10^{4}$
1000.0rg	$0.00102^{0.00005}_{0.00005}$	$(3.71^{0.04}_{0.04}) \times 10^{-3}$	$(6.4260^{0.0010}_{0.0010}) \times 10^{4}$
5000.0rg	$0.00530^{0.00022}_{0.00022}$	$0.0184^{0.00018}_{0.00018}$	$(5.6320^{0.0010}_{0.0010}) \times 10^{4}$
10000.0rg	$0.0100^{0.0005}_{0.0005}$	$0.0374^{0.0004}_{0.0004}$	$(5.5121^{0.0010}_{0.0010}) \times 10^{4}$
50000.0rg	$0.0485^{0.0024}_{0.0024}$	$0.1850^{0.0019}_{0.0019}$	$(4.9767^{0.0010}_{0.0010}) \times 10^{4}$
100000.0rg	$0.101^{0.005}_{0.005}$	$0.369^{0.004}_{0.004}$	$(4.7146^{0.0010}_{0.0010}) \times 10^{4}$

Table 1: Parameters for the fitted Gaussian function

h_{max}	offset	χ^2
100.0rg	$0.95^{0.29}_{0.29}$	17.9359
500.0rg	$0.89^{0.29}_{0.29}$	9.4053
1000.0rg	$1.0^{0.4}_{0.4}$	8.8350
5000.0rg	$0.86^{0.30}_{0.30}$	8.9959
10000.0rg	$1.2^{0.4}_{0.4}$	6.9433
50000.0rg	$0.75^{0.28}_{0.28}$	6.0829
100000.0rg	$1.5^{0.4}_{0.4}$	6.4035

Table 2: Parameter for the fitted Gaussian function

8 Results

To get an overview of how, the simulated time delay influences a given pulse profile of an ultra luminous X-ray source, I folded the probability figure 9 with a given Gaussian function. The Gaussian function hence describes a very narrow delta-peak function and has the starting parameters $\sigma = 0.1$ sec, $\mu = 0.5$ and a pulse period of one second. This very narrow delta-peak function describes the expected pulse profile of the ULXs which harbor a neutron star in the center (Fürst et al., 2016). For the pulse profile I multiplied the given Gaussian function with the probability after that I restricted the pulse period of one second and therefore subtracted all values which lay between one second and two second (figure 14) by minus one and the values which lay between two and three by minus two. After that I binned the x value by 0.001 and added all values which are in one bin to get the final pulse profile. Figure 14 show the light curves for the given heights of the cone h_{max}. Up to an height $h_{max} = 10000$ rg the pulse profile would not be influenced very much by the folding such that it would influence the pulse profile. For a height $h_{max} = 100000$rg the pulse profile gets influenced by the folding. Figure 15 shows the given pulse profile before the folding (black) and the pulse profile after the folding (blue). It is clear, that the very narrow delta-peak function gets smoothed by the folding and becomes more sinusoidal. The simulations (figure 15) hence show the in the theory (chapter 5.2) expected behavior. To explain the observed pulse profile (figure 7) of the three known ULXs which harbor a neutron star in the center, the simulations have to be more precisely.

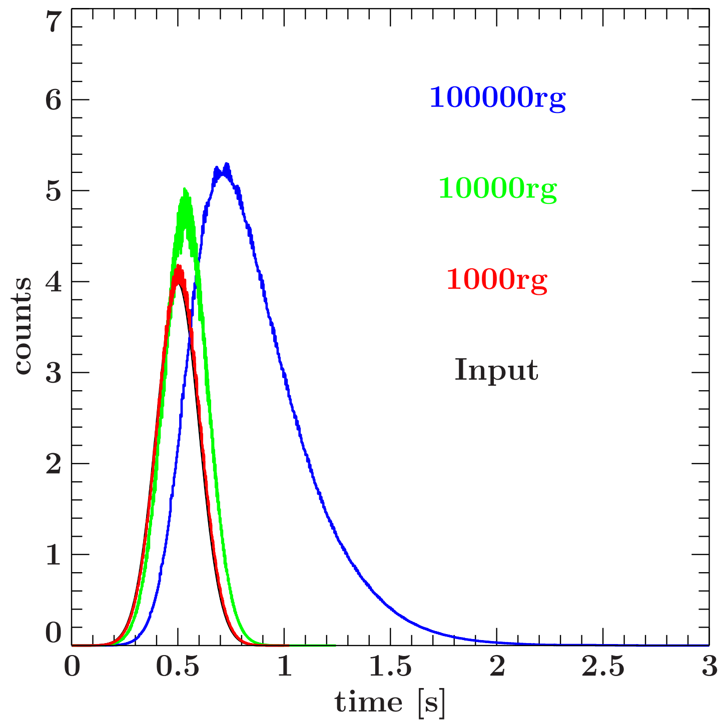

Figure 14: light curves for different heights of the cone h_{max}

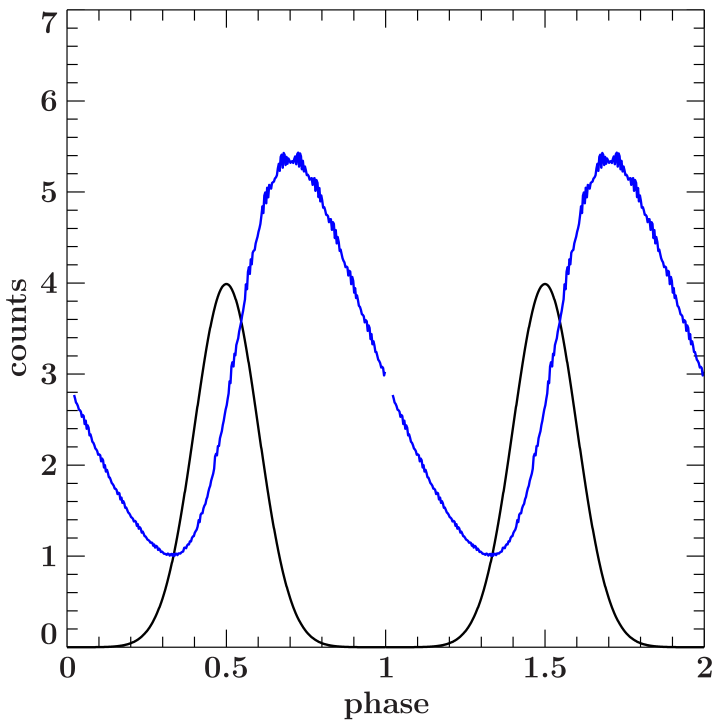

Figure 15: pulse profile for $h_{max} = 100000rg$ blue and gauss input black

9 Conclusion

To summarize the results of my simulations and what I found out about the time delay caused by scattering inside these cones, I start with the time delay simulations. To begin with the time delay, in figure 8 we can see, that we can get a time delay up to one second for a height $h_{max} = 100000rg$ of the cone. The maximum time delay depends on the height of the cone and not on the inclination of the observer or the open angle like the amount of scatterings.
The next point I want to mention are the Gauss function fits. To get an overview of how big the time delay can be, I fitted Gauss functions on the data. The gauss function did not describe the time delay functions very well but it allowed us to get an overview of the behavior of the time delay curves. To describe the time delay curves exactly, we need a more complex function. But for an overview the gauss function is good enough. After the simulations for the time delay I had a rough idea how the time delay could influence the expected very narrow delta-peak pulse profile of these three ultra luminous X-ray sources, which hosts a neutron star in the center. The goal of this thesis was to explain the observed sinusoidal pulse profile (figure 7) of some sort of ULX. Figure 15 shows that we can get a sinusoidal pulse profile, when we fold the input signal with the probability. To explain the observed sinusoidal pulse profile of these three ULXs we have to improve our model and further simulations are needed.

10 Outlook

In my simulations I only did estimates about how scattering in cones take place. Therefore, there it is still quite some work to do. First and foremost it is still not clear how high cones of ultra luminous X-ray sources can be. A detailed analysis for this parameter is necessary to explain time delay caused by scattering inside these cones, which depends on the hight of the cone. Apart from that I assumed a constant outflow without clumpy clouds. This assumptions was necessary because an outflow with clumpy clouds would be far to much for this work. Clumpy clouds inside the cones could influence the number of scattering and the time delay of photons.

Another important fact is, that at the moment there are only three known ultra luminous X-ray sources NGC 7793 P13, NGC 5907 and M82 X-2, which harbor a neutron star in their center. With further observations of ULX we will be able to identify further ULX which harbor a neutron star in there center and get more informations about these accreting systems.

Further improvement of the simulations would be if we use general relativity for the calculations of the photon trajectories. I am sure, further observations of already known ULX, improvements in the theoretical simulations and the discovery of new ultra luminous X-ray sources, which may harbor a neutron star in the center, will allow us to improve out knowledge about this interesting sort of X-ray emitting sources.

In addition to that systematic search in parameter space for system parameters will make it able to produce the sinus profile which has been observed by Fürst et al. (2016). Also it would be necessary to fit the simulated pulse profile to the observed pulse profile of the ULXs.

Satellite projects like the eROSITA all sky survey and pointed observations with the Athena X-ray observatory will help to explain and answer some existing questions about ULX. Maybe in the end we will be able to explain the final question, if the majority of these sources exceed the Eddington luminosity by a few times or if not because they harbor a so called intermediate mass black hole in the center.

11 Attachment

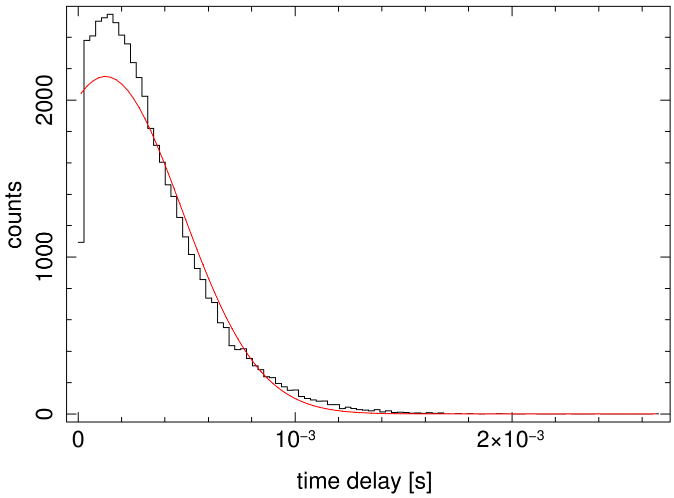

Figure 16: Inclination 10 deg, h_{max} = 100rg, open angle 5 deg and 1×10^6 photons

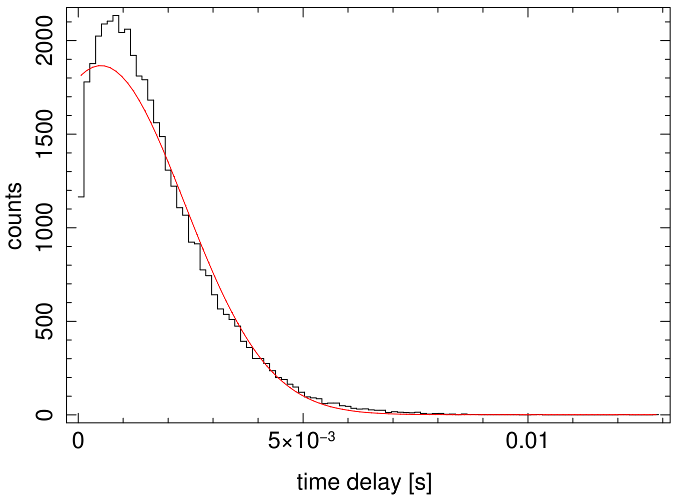

Figure 17: Inclination 10 deg, h_{max} = 500rg, open angle 5 deg and 1×10^6 photons

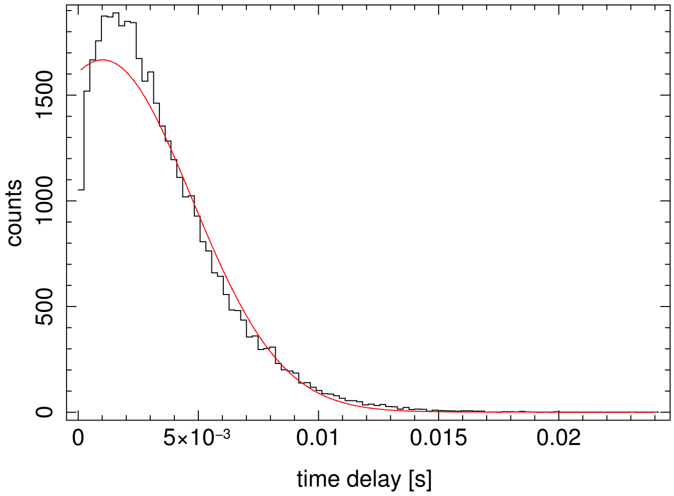

Figure 18: Inclination 10 deg, $h_{max} = 1000$rg, open angle 5 deg and 1×10^6 photons

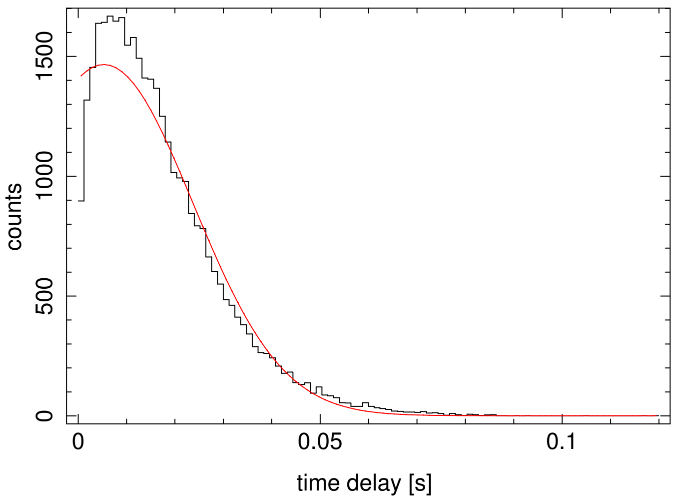

Figure 19: Inclination 10 deg, $h_{max} = 5000$rg, open angle 5 deg and 1×10^6 photons

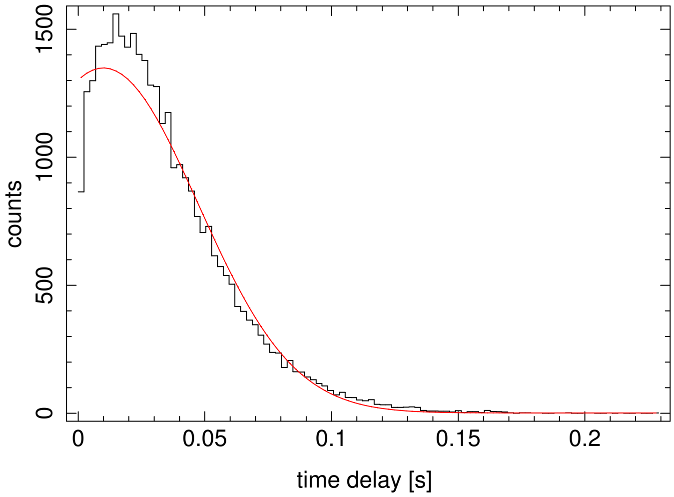

Figure 20: Inclination 10 deg, h_{max} = 10000rg, open angle 5 deg and 1×10^6 photons

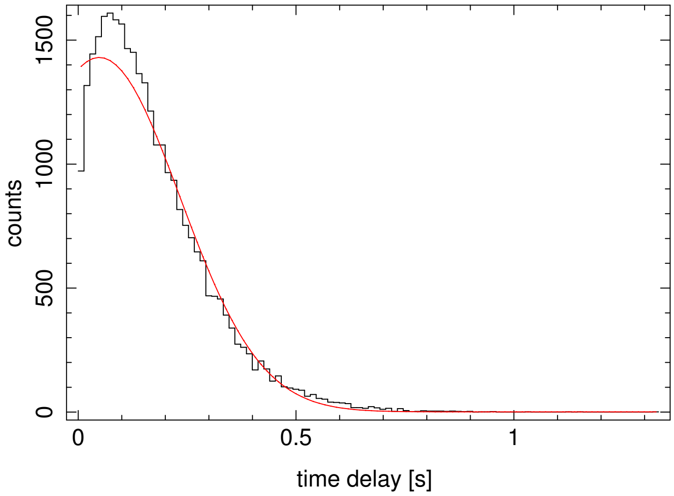

Figure 21: Inclination 10 deg, h_{max} = 50000rg, open angle 5 deg and 1×10^6 photons

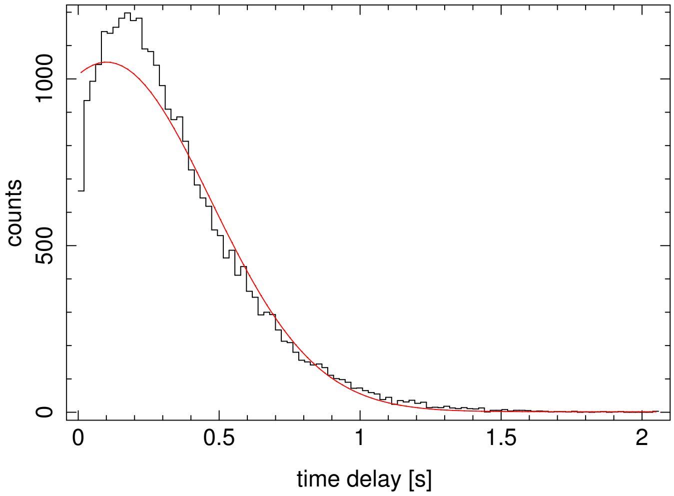

Figure 22: Inclination 10 deg, $h_{max} = 100000$rg, open angle 5 deg and 1×10^6 photons

12 References

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14 Eigenständigkeitserklärung

Erklärung

Hiermit erkläre ich, diese Arbeit selbständig angefertigt und keine anderen, als die angegebenen, zugelassenen Hilfsmittel verwendet zu haben.

Ort, Datum

Alexander Adolf Ernst Karl Reichel