Unvealing the Secrets of Neutron Stars

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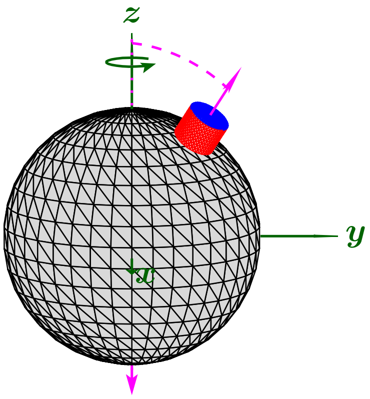
Summary

I have spent 8 weeks at the Remeis Observatory in Bamberg, Germany, working on X-ray astrophysics. Starting with some research on the physical model of a neutron star, I changed to timing analysis, extracting pulse profiles from around 5,000 observations carried out with the proportional counter array (PCA) of the RXTE satellite. Besides gaining some insight into high energy astrophysics, I considerably improved in organising my work and learned to value a comfortable working environment.

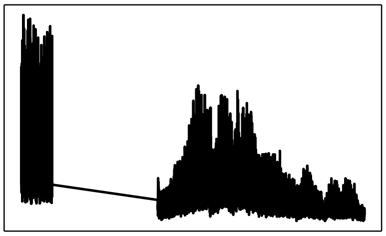
Pulsars are among the most extreme - and least well understood - objects in the universe. Governed by the strange laws of Quantum Mechanics and General Relativity, they reveal their existence only in the high energetic part of the electromagnetic spectrum, especially in X-rays. Since this radiation is almost completely shielded by the atmosphere, observations are carried out with detectors mounted on spacecraft.

One of those satellites was the Rossi X-ray Timing Explorer (RXTE), which took among other data lightcurves of known pulsars with a relatively high time resolution of 125 ms. Pulsars show periodic variations in flux because they accrete material from binary companions at their magnetic poles, so that X-rays are emitted from these accretion columns. Due to the neutron star's rotation, a lighthouse effect generates a characteristic pulsation.



Geometric model of a neutron star, one accretion column is visible. The actual appearance would be quite different due to lightbending effects.

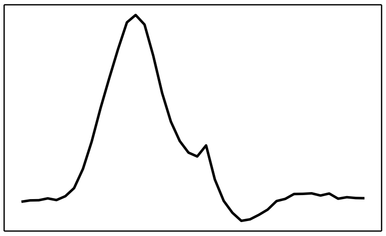
This pulse profile can reveal a lot of information about the geometry and physical properties both of the neutron star itself and the accretion columns. My supervisor at the Remeis Observatory in the beautiful German town of Bamberg has written a model that gives for a set of physical parameters the corresponding pulse profile.



Lightcurve of Her X-1 with gap and underlying flux variation. This observation spans around 1.5 ks and has count rates of between 200 and 3500 photons per second.

My first goal was it to try and find the points in parameter space which could generate a pulse profile measured by RXTE. Due to the high non-linearity of the model, a conventional χ^2-minimization algorithm would inevitably fail if the parameters were allowed to vary over the whole range, so the first step was to generate a number of pulse profiles, so that the location could be somewhat constrained. After computation of 1.4m profiles, a conventional fitting technique was employed to find the profiles that showed the best agreement with the observed data (a fit was required because parameters like an absolute offset resp background and the influence of different kinds of radiation are unknown). The result was somewhat satisfactory, but there remain problems: The errors in the pulse profile are not well understood, hence it is not possible to tell whether our fit was actually physical or rather fitted to noise. Furthermore, the computation of the fit took days on a computer cluster with some 30 cores, so that this technique is not suitable to be applied on the around 5,000 pulse profiles we have from RXTE PCA (around 80 sources).

Hence, a second approach taken by me was to try and find global properties of pulse profiles that can be mapped onto the parameter space and allow a fast way to constrain search regions. This proved to be extremely difficult, in part because the quality of the profiles was not perfect. Hence we realised that it was necessary to do the profile extraction again with improved quality.



The lightcurve folded on the period gives the pulse profile, i.e. a relationship between phase and count rate.

In order to achieve this, I used a technique known as epochfolding. Its basic idea is to take the observed ligthcurve, guess a period, and then fold the lightcurve onto this period. Depending on how good the guess was, the profile will show a certain amount of noise or actual information. A good measure is the χ^2-value of the profile with respect to a zero signal, so that we expect a maximum χ^2 for the best period guess. This simple idea has some great advantages over a Fourier technique, especially when it comes to highly non-sinusoidal profiles as are regularly observed for pulsars, and when gaps in the lightcurve are present. Problems arise if certain features in the lightcurve produce spikes in the χ^2-landscape, which can be higher than the real peak, and if harmonics of the peak show higher statistics due to binning and other effects. Therefore, I wrote code that allows to filter the χ^2-landscape for certain peak shapes, employing a useful technique known as bayesian block analysis. Furthermore, instead of just using a discrete maximum value in the peak, a fitting routine was implemented. All these measures will still fail if the data quality is extremely poor. Hence it was necessary to implement some kind of evaluation of the goodness of the final pulse profile.

My final result is a set of almost 2,000 pulse profiles that can with high confidence said to be of high quality. Furthermore, the other 3,000 pulse profiles are mostly of better quality than before and the pulse period determination has been improved. Additionally, the code written by me has been included in a software package used by X-ray astronomers, so that pulse period determination and timing research in general will hopefully be more convenient, more reliable and more flexible with these functions.

I think I have learned a lot about high energy astronomy in the course of my 8 week internship at the Remeis Observatory in Bamberg and have made good progress in my programming abilities. More importantly, however, I have greatly improved on the organisation of my work and the planning of a longer project. Furthermore, the really good working atmosphere at the institute has boosted my confidence to work in teams, get help if necessary and present my results concisely. An additional benefit of this great experience is my improved ability to cope with drawbacks, as they are inevitable in real world research.