Finding Periodicities in X-Ray Observations made by XMM Newton in Timing Mode.

Joseph Ware, Supervisor Diego Altamirano

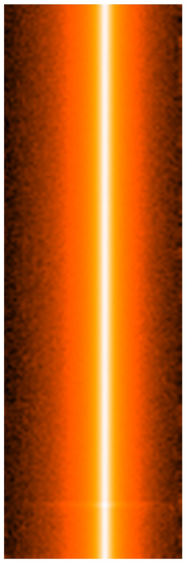
Due to the atmosphere blocking x-rays, x-ray astronomy as a field is much younger than other forms of astronomy, with the Crab pulsar- a neutron star within the Crab nebula- only being discovered in 1968 signalling the birth of the field. Neutron Stars- incredibly dense remains of stars which have violently shed their outer surfaces- and Black Holes- even denser stellar remnants, so heavy that even light cannot escape them- are the key sources studied by x-ray astronomy: their densities means that objects falling into them are accelerated to high speed and rapidly squeezed together, producing the incredible temperatures necessary to emit x-rays. X-ray astronomy is therefore a useful tool for studying these dense objects, some of the most violent places in the universe; neutron stars can weigh as much as 10-30 Suns, squeezed into a ball 10km across and spinning as much as 700 times per second, meaning their surfaces are travelling at an appreciable fraction of the speed of light, some even have such strong magnetic fields that they emit a focused beam of radiation from their poles, while black holes spaghettify and absorb all matter that comes too close.

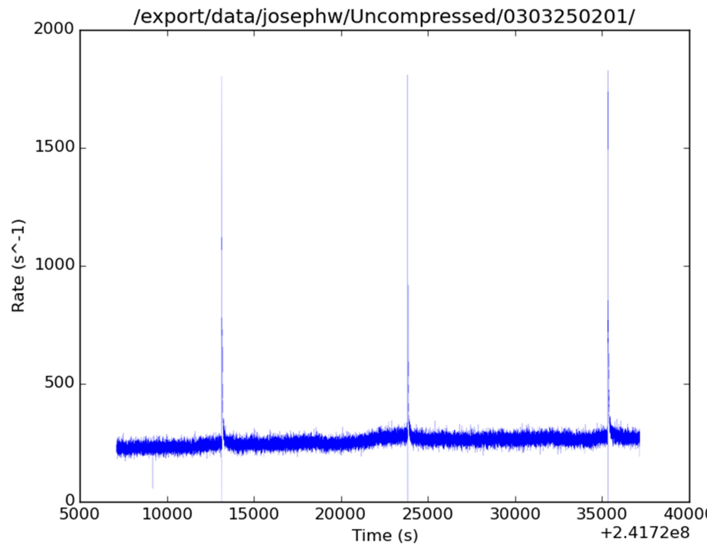
These incredible objects are observed, potentially over thousands of light years (the Crab pulsar for example being over 6600 light years away- 40 billion million miles) by satellites like XMM Newton, a European Space Agency satellite launched into Earth's orbit in 1999. Newton has three telescopes on board, two utilising pixels like those in a digital camera- MOS CCDs (Metal Oxide Semiconductor Charge Coupled Devices) which work well for medium energy x-ray photons, while a third uses a different form of CCD- pn CCD which uses a semiconductor coupling and also works well for higher energy x-rays. Regardless of the telescope used, the capture is similar to using a digital camera with a long exposure time; the shutter is opened and photons strike different 'pixels', building up an image. Unlike a camera however, the number of photons flowing is in much lower (potentially as low as on the scale of photons per second- on the order of a millionth of a millionth of a per cent of how many enter our eyes during the day) and the camera not only records how many photons hit each pixel, but also their individual energies and their time of impact. For the brightest sources, the camera can even purposefully turn off some of the pixels so that instead of a grid, the camera acts as a series of lines, allowing for less information about the photon to be recorded (losing its position in one dimension) but allowing for the camera to know with much more certainty when the photon impacted- this is known as Timing Mode.

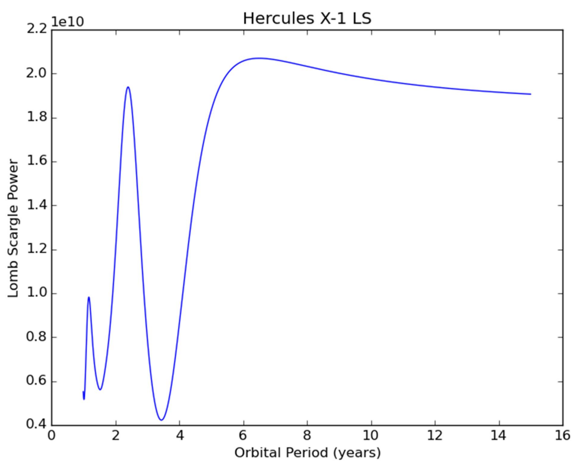
When this Timing Mode data is safely returned to the ground, it can be reconstructed into 'pictures' like in Fig 1., or instead plotted as a graph of brightness against time, known as a Light Curve, like in Fig 2. From these light curves, the periodicities such as the spin of a Pulsar can be reconstructed through the use of Fourier Transforms (Fig 3.)- computer programs that plot sine-waves to the data. While the Timing Mode on the pn CCD can resolve as little as 7 millionths of a second, the data is usually 'binned' into larger chunks before this occurs for various reasons- noise may dominate over a short period but be drowned out in signal in larger bins, computer programs to transform the data run quicker with smaller amounts of data and because while the programs are limited by the time between observations, it is unlikely to find signals on the upper end of the resolution- a ball the size of a neutron star spinning at a rate of once every 3.5*millionths of a second would be travelling at almost 1500 times the speed of light.

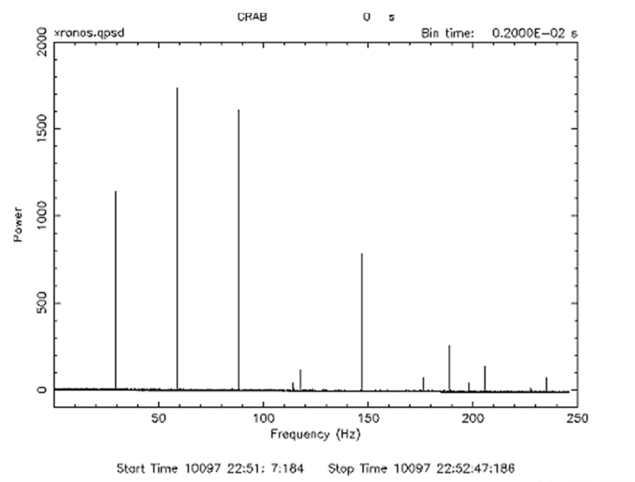
On the other end of the data, the minimum rate of periodicity that can be found is that of one revolution over the entire data set, and therefore other tools allow for investigating these better- this may be the orbit of a companion star (like Hercules X-1's, which orbits every 1.7 days) or planet, or the wobble of a disc of matter falling into the object (again like X-1's, which takes 35 days). The Fourier transform used for the above does not work well with data with gaps in and therefore the

Lomb-Scargle periodogram, another Fourier transform that is not as well studied statistically but that allows for gaps in data must be used to allow for the longest time to be examined.









Figs 1-4, clockwise from top left.

Fig 1: A 'trace' of a Timing Mode observation- the long axis is time while the short axis is a spatial dimension. The brightness of a pixel is a heat map of total photon incidence per second.

Fig 2: A Light Curve of the same observation. The x-axis is time and the y-axis number of photons incoming per second; the spikes are 'Type 1 X-Ray Bursters', periodic (but not regular) in falling matter momentarily igniting nuclear fusion on the surface of the neutron star. This is therefore definitely a neutron star, since black holes do not have a surface.

Fig 3: A Fast Fourier Transform of the Crab Pulsar- shown is the 33Hz spike of the rotation of the pulsar and also its harmonics. Source: https://heasarc.gsfc.nasa.gov/docs/xte/learning_center/xray_pulsar.html (retrieved 17/04/18)

Fig 4: A Lomb-Scargle Periodogram of 15 observations accounting for 3.6 days' worth of total observation time over 15 years. An extreme and likely unhelpful application of the Lomb-Scargle periodogram to show its capability.