Chandra Observations of Zeta Pup

PROBING FOR ROTATIONAL MODULATION OF THE X-RAY FLUX AND HARDNESS IN A SUPERGIANT O STAR

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INTRODUCTION

Hot stars such as Zeta Pup are strong X-ray emitters but the precise mechanism causing their X-ray emission is unclear. In this project we examine the temporal behavior of the X-ray emission from this star. If the X-rays are formed far out in the stellar wind, we would expect the X-ray output to fluctuate randomly. If the X-rays are formed close to the stellar surface (e.g. in magnetic structures), we would expect X-rays to vary clock-like on a rotational time scale. Recent work (Howarth and Stevens, "Time-series photometry of the O4 I(n)fp star ζ Puppis") has identified a 1.78-day rotational period for this star, so we folded the data on this time scale to try to identify rotationally-modulated variation.

In addition to examining the overall X-ray photon count rate, we evenly divided the data into short-wavelength ("hard") X-ray counts (from high-temperature gas) and long-wavelength ("soft") X-ray counts (from low-temperature gas). This allowed us to construct the "hardness ratio" by calculating the difference between the hard and soft count rates and dividing by the total count rate.

When examining the folded total, hard, soft, and hardness ratio data we found no case where there was unambiguous evidence for variation on the rotational time scale.

TERMINOLOGY/EQUIPMENT

Chandra
- Satellite telescope designed to detect X-rays

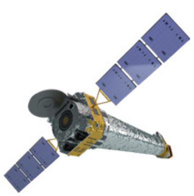
CIAO - "Chandra Interactive Analysis of Observations"
- Software designed to interface with data obtained by Chandra

ACIS - "Advanced CCD Imaging Spectrometer"
- Detector that collects high energy photons
- High resolution for more precise energy distinctions

MEG - "Medium Energy Grating"
- Measures photons with wavelengths between 2.5 and 31 Å

LibreOffice Calc
- Data manipulation software

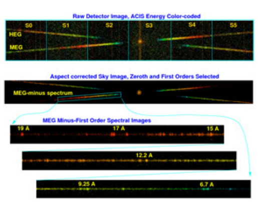
Zeta Puppis (Zeta Pup)
- Blue supergiant star

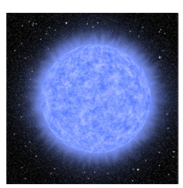


Chandra Telescope

Our Sun vs Zeta Pup

	The Sun	Zeta Pup
Distance from Earth	~8.3 light-minutes	~1,000 ly
Stellar Wind Speed	~400 km/s	~2250 km/s
Surface Temperature	~5,700 K	~39,000 K
Mass (Solar Masses)	1	60
Radius (Solar Radii)	1	20





Artist's representation of a blue supergiant.
Source: https://en.wikipedia.org/wiki/Zeta_Puppis

Twelve observations were taken by Chandra from 1 July to 24 August, 2018 and a colleague (Dr. Jennifer Lauer, Harvard-Smithsonian Center for Astrophysics) subsequently divided these observations into ~9,000 second intervals. This was chosen out of convenience as a result of all of the observations being approximate integer values of this time interval.

PROCEDURE

ANALYSIS

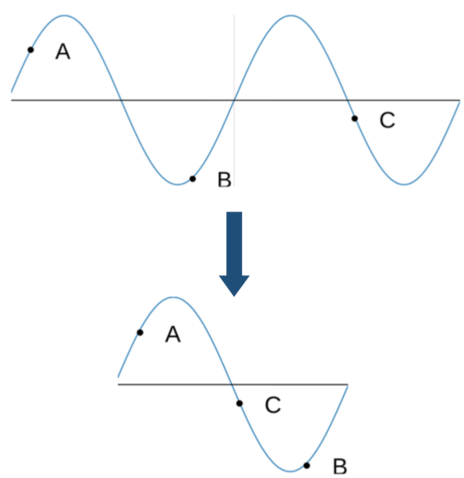
After extracting the events, I organized the X-ray photon counts (counts) into three categories: total counts, high energy ("hard") counts, and low energy ("soft") counts per ~9,000 s interval. The split between hard and soft was done at 9 Å to create an approximately equal number of hard and soft counts.

The next step was to obtain the count rates for total, hard, and soft counts to homogenize any disparity in the time intervals of the observations. However, because Chandra marks beginning and end times of observations but the observations were broken up further into those time intervals (bins), I had to estimate the average time that the counts were taken in each bin.

I accomplished this by taking the average time of each bin in each observation, and calculating the midpoint between the beginning of the bin and the end of the bin. That "mid-time" was then used in the final steps of the data analysis.

From there, I calculated the hardness ratio by dividing the difference between the hard and soft count rate and the total count rate. This ratio indicates a kind of "temperature" to the X-rays wherein a higher hardness ratio is higher energy X-rays (and are thus "hotter"). This also gives another possible dataset to view any rotational aspect in the X-ray spectra.

Using the mid-times for each bin, I then phase-folded each bin such that every bin would appear on a single 1.78 day period as identified in 2018 (see figures below).



ERROR ANALYSIS

Poisson Error Analysis was used for the relative error for the counts. This is given by:

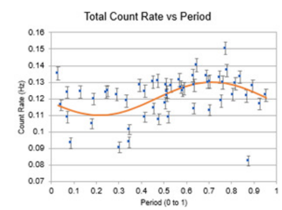
$$\text{Relative Error for Counts} = \frac{\sqrt{\text{Number of Counts}}}{\text{Total Counts}}$$

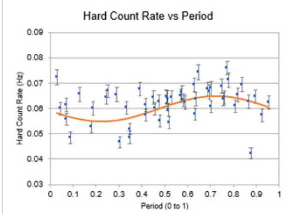
The Hardness Ratio Error was calculated using standard Propagation of Uncertainty given by the general form:

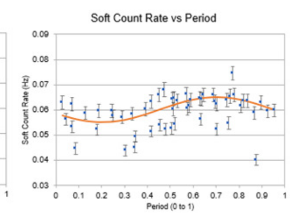
$$\text{Error} = \sqrt{\left(\frac{\partial F}{\partial x}\right)^2 (\Delta x)^2 + \left(\frac{\partial F}{\partial y}\right)^2 (\Delta y)^2 + \ldots}$$

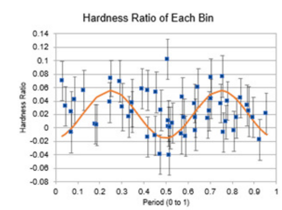
RESULTS

With the analysis complete, the last thing to do was graph everything as see if a pattern emerges.









The orange sine waves were made with an iterated use of a best-fit program in Linux. The R^2 value for the total, hard, and soft count rates are approximately 0.20 and the R^2 value for the hardness ratio is 0.07.

These values indicate that while there may be a very weak variation of the overall X-ray flux as a function of the rotational period, the X-ray color (hardness ratio) is even less effected by the rotational phase.

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