Examining the Emission Geometry of SXP 348 with *Polestar*

The SMC

The Small Magellanic Cloud (SMC) is a dwarf galaxy in the Local Group. This galaxy makes an ideal laboratory for studying X-ray pulsars (XRPs), as it is relatively nearby with a well-known distance (~ 62 kpc) and the population of high-mass X-ray binaries (HMXBs) is comparable in number to that of the Milky Way, despite the SMC containing roughly one-hundredth of the total mass of the Milky Way. Curiously, almost all of the HMXBs in the SMC are Be X-ray binaries, where the donor star is classified as a B star with emission lines in its optical spectrum due to a large circumstellar disc. This disk is responsible for providing the material that will eventually follow magnetic field lines down towards the surface of the neutron star and release gravitational potential energy in the form of the pulsed X-ray emission that we observe.

The purpose of this study is to characterize the SMC pulsar population by extracting folded pulse profiles from all available archival X-ray data and fitting those profiles with *Polestar*, the XRP modeling software we have developed. The aim of this fitting is to establish new bounds on important XRP parameters, including the inclination angle of the neutron star, the location of the hot spots, the geometry of the emission region, and a critical luminosity that marks the formation of an accretion column.

Chandra and the SMC

Since first light in 1999 the *Chandra* X-ray observatory has performed over 350 observations with a section of the SMC in the field of view. We have collected all of these observations through the summer of 2019 and produced event lists, along with source and background light curves for each unique X-ray source ever detected by *Chandra* in the SMC. To facilitate this process we have created a turn-key pipeline written in *Python* in conjunction with the *CIAO* X-ray analysis software to treat raw *Chandra* data, extract event files and light curves, identify periodicities, create folded pulse profiles, and fit those profiles with *Polestar*. In conjunction with this *Chandra* data, *XMM-Newton* data was used as well. We are currently in the process of incorporating other existing X-ray data from RXTE, *Swift*, *Suzaku*, NICER, and *NuSTAR*.

Polestar

Polestar is a physically-motivated geometric model of an XRP we have written in *Python*. It has a relatively small number of parameters in order to facilitate inexpensive fitting to folded pulse profiles. Fitting large numbers of profiles of the same object we hope to get a better understanding of the geometry of the emission region and the orientation of the neutron star. With the addition of fan and pencil beam emission components it also offers the possibility of a novel technique for determining a critical luminosity for a given pulsar.

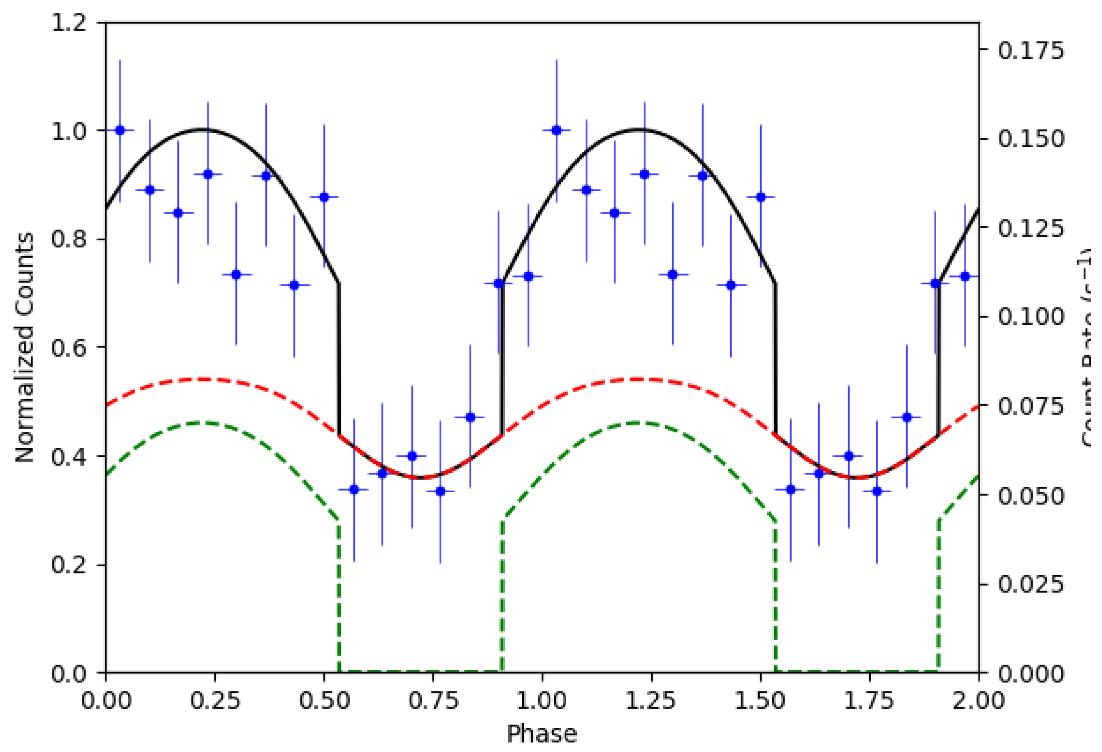


Figure 1. *Polestar* model fit corresponding to the geometry shown in Fig. 5a, with $i = 54^{o}$ and theta = 20^{o}. The data, with error bars indicating count-rate uncertainty and bin size, are in blue. The model fit is in black, with the contributions from the two hot spots in red and green dashed lines. This folded pulse profile of SXP 348 is from *Chandra* ObsID 444.

SXP 348

First detected by *BeppoSAX* in 1998, SXP 348 is an X-ray Pulsar in a binary system with a Be optical companion. Due to its proximity to a calibration target, *Chandra* has observed the region containing this source over 80 times. The final detection of pulsations from this source came in 2006, and the final detection as a point source was in 2011, despite being in the FOV in observations through 2019 (Fig. 2).

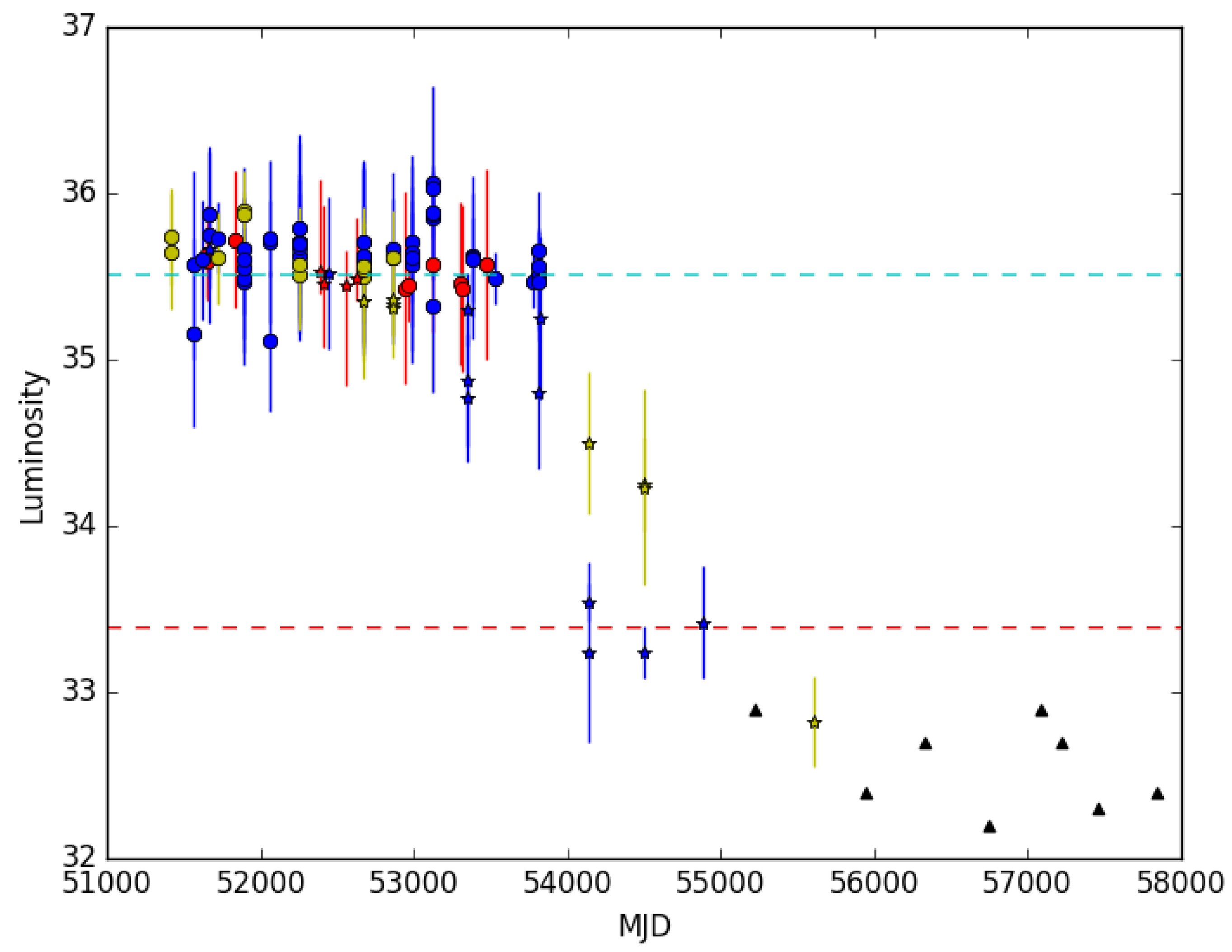


Figure 2. All of the detections of SXP 348 with *Chandra* and *XMM-Newton*. In this plot red indicates *XMM-Newton* EPIC-PN, blue is *Chandra* ACIS-I, and yellow is *Chandra* ACIS-S. The circles indicate detection of pulsations and the stars indicate detections of the source without detected pulsations. The black triangles are upper limits for non-detections. The dashed lines represent the propeller line for various magnetic field strengths following the formula found in Christodoulou (2016) for a NS with a mass of 1.4 solar masses, a radius of 10 km, and a period of 342 s. The red line is for B = 10 TG and the cyan line is from Table 3 in Klus (2014) as their calculated lower limit for this source at B = 115 TG. Luminosities are displayed on a logarithmic scale with units of erg s^{-1}.

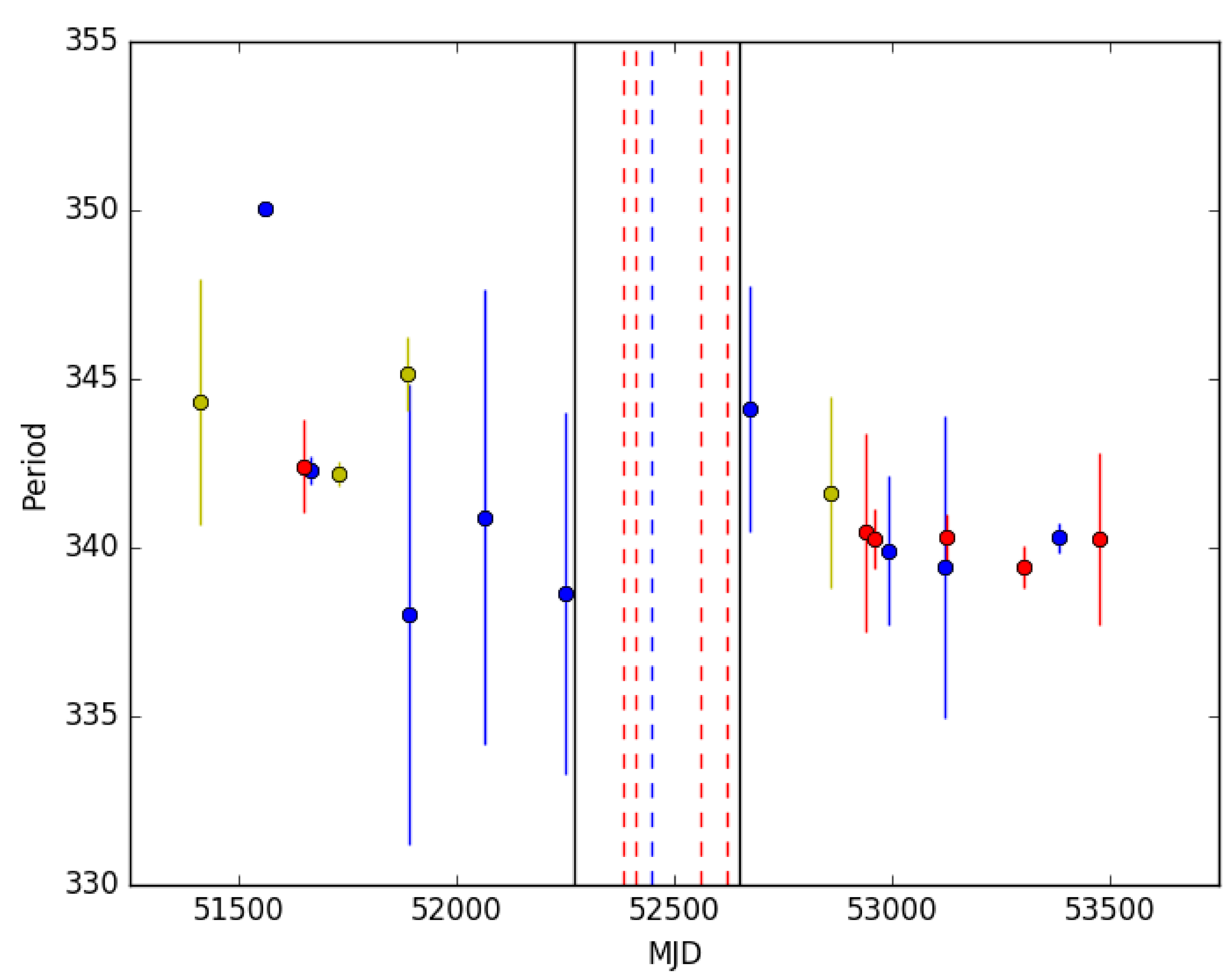


Figure 3. The change in period for SXP 348 over time. As above, blue indicates *Chandra* ACIS-I, yellow indicates *Chandra* ACIS-S, and red indicates *XMM-Newton* EPIC-pn. The span in 2002 where the *Polestar* fit parameters changed is bookended by solid black lines. The red and blue dashed lines indicate observations where the source was detected but lacked significant pulsations. For clarity, observations made on the same or consecutive days have been combined. The error bars on the periods have been added using a Monte Carlo technique we devised specifically for this study.

A Change in Geometry

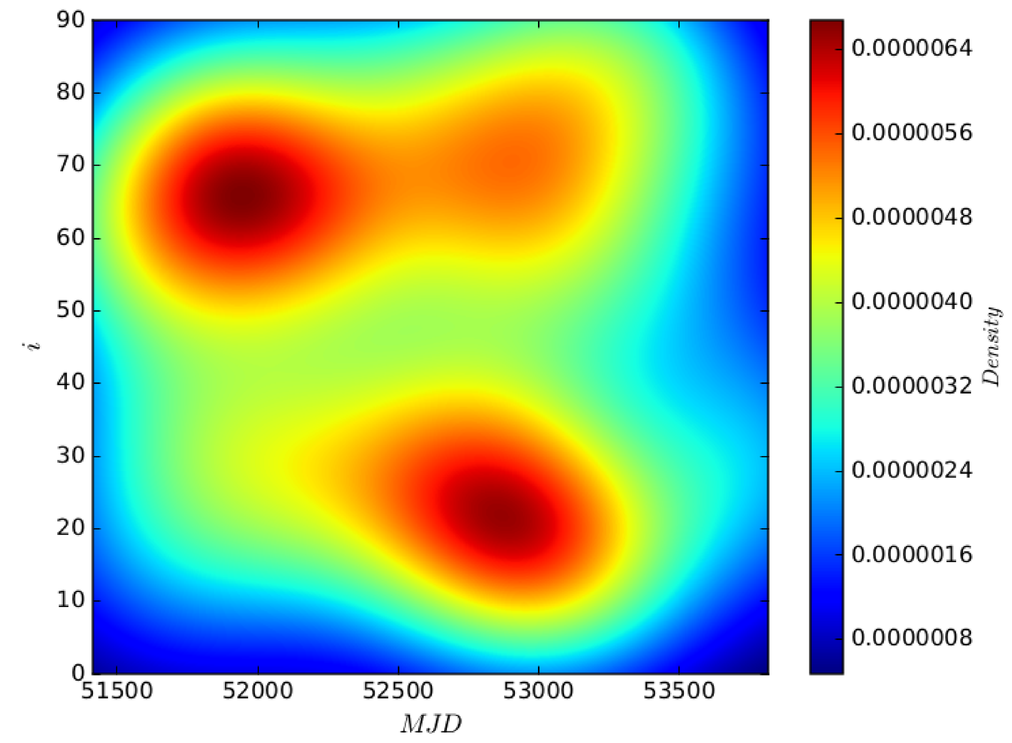
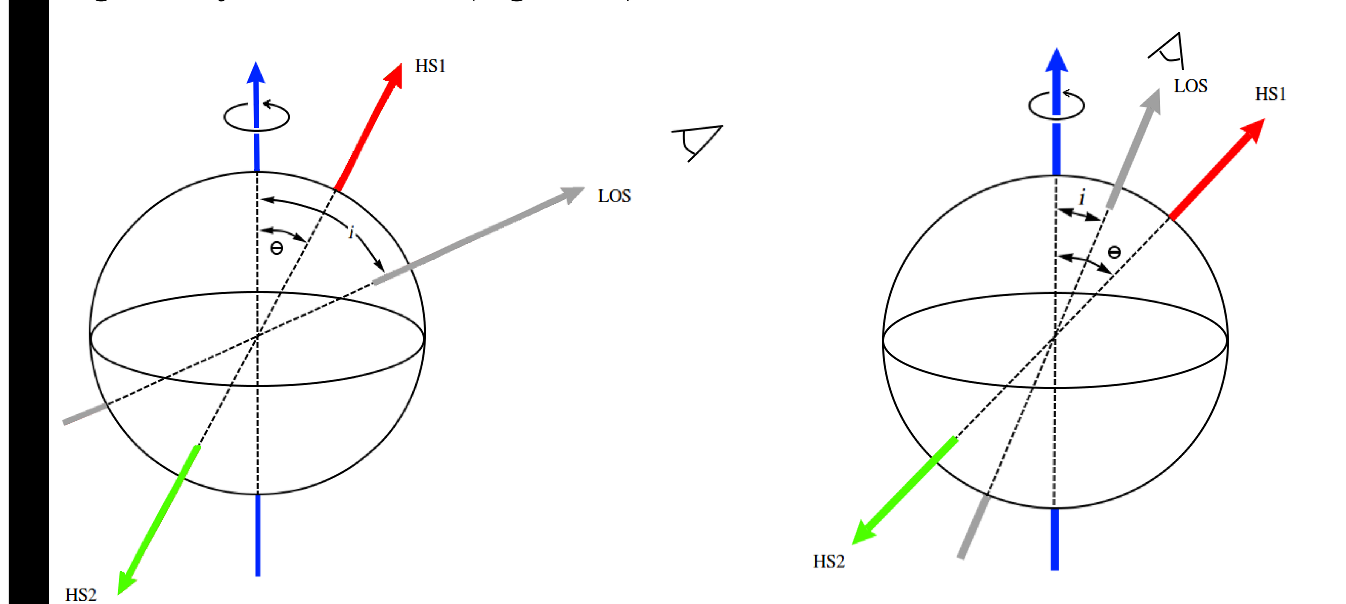


Figure 4. A population density plot of the value of the inclination angle (i) over time for all 53 Polestar fits of SXP 348. There is a clear change in preferred values occurring in conjunction with an event in 2002 (~ MJD 52300) during which significant pulsations ceased.

For nine months in 2002 SXP 348 ceased producing significant pulsations despite exhibiting a consistent X-ray luminosity. Once pulsations resumed, the best-fit Polestar parameters changed markedly (Fig. 4). This implies that some event occurred which fundamentally altered the accretion pattern or emission geometry of this source (Figs. 5a,b).



Figures 5a,b. The geometry corresponding to the best-fit Polestar parameters before (*left*) and after (*right*) the event in 2002. The blue line denotes the spin axis, the red and green vectors are the two hot spots, and the grey vector is the line of sight to the telescope.

Conclusions

Other X-ray pulsars have exhibited the same phenomenon, with an event marked by pulsation cessation without a change in luminosity, including SXP 1323 and M82 X-8. The fitting performed in this study is the first indication that the disappearance of pulsations could be linked to a long-term change in the accretion pattern or emission geometry rather than obscuration of the pulsations by accreting matter or an envelope of ionized material. In the future it would be informative to fit profiles from these other sources with *Polestar* to see if their parameters changed before and after their pulsation cessation events as well. While it is unlikely that the change in parameters are physically accurate (i.e. the angle between the spin axis and the line-of-sight axis actually changed significantly), this fitting is still a useful tool in determining that some fundamental change in the system did occur.

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