University of Cape Town

Department of Astronomy

Compact Binaries Report

Course: Accretion Binaries (ACB)

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Introduction

Cataclysmic variables (CVs) are described as binary systems consisting of a white dwarf (WD) primary, and a low mass main sequence star. In many systems, mass is accreted onto the white dwarf from the secondary star; and in many of these systems, the white dwarf will have an accretion disk. Accretion occurs when the secondary star fills its Roche lobe such that stellar material flows toward the primary star. For WDs with a magnetic field $\geq 10^5$ Gauss, the accretion flow will exhibit different patterns that the non-magnetic counterpart [2]. Accretion in these systems does not come in the form of a disk, but instead is channelled at the poles of the WD. The material then forms bright hotspots at the poles due to a high influx of stellar material rapidly collapsing onto the WD surface. The collision forms shocks that generate immense heat, causing the luminosity of these points to be very high with high amounts of x-ray emission. Magnetic Cataclysmic variables are categorised into two groups: polar and intermediate polar. In polars, the WD has a very strong magnetic field which causes the accreted stellar material from the ballistic stream to flow along the magnetic field lines and funnel to the magnetic poles forming accretion streams. At the poles, cyclotron radiation occurs producing X-rays. Accretion only being at the poles prevents the formation of an accretion disk. Polar systems have tidally locked stars where their orbital periods are synchornised. Stars of this type are called *AM Herculis* stars. In intermediate polars, the WD has a weaker magnetic field of $\sim 10^6 - 3 \times 10^7\ G$. The WD's magnetic field is not fully able to prevent the formation of an accretion disk; so stellar material is threaded from the inner regions of the accretion disc and funnelled to the magnetic poles of the WD. Stars in this system do not have a synchronised orbital period, and the WD has a spin period shorter than the orbital period. [1]

Literature review of the target: J1912-44

`J1912-44` is a white dwarf with an M-dwarf companion discovered recently by the eROSITA telescope during an all-sky survey between 2020 and 2021. It has the position $RA2000 = 288.057°$ and $DEC2000 = -44.179°$ [5]. The WD has an orbital period of 4.03 hours and a spin period of 5.32 minutes. Given the current understanding of CVs and the research project focusing on magnetic CVs, one would be quick to assume the system is an example of an intermediate polar. The existence of pulses in the light curve suggest a different category entirely. This non-eclipsing binary system bears a strong resemblance to AR Sco, a WD pulsar, also with an M-dwarf companion [3]. A WD pulsar system is composed of a rapidly-spinning WD and a late-type main sequence star that exhibit strong pulsed emission on the WD spin period, where the exact source of the pulses is unknown. The pulsed emission can be detected from radio to X-rays. Binary systems are an important factor in the ability of the WD to produce pulsations where past accretion may have led to the observed fast spin. Free electrons from the secondary star are accelerated to near relativistic speeds as they flow along the magnetic fields of the WD, which generates non-thermal (synchrotron) pulsed emission [4]. Observations using a 4.0 m telescope and 1.0 m telescope at the South African Astronomical Observatory (SAAO), confirmed that the target showed similar spectral characteristics to AR Sco; namely strong Balmer line and neutral helium line emission as well as the optical spectrum displaying a blue continuum (attributed to the WD) with a red spectrum (from the M-dwarf) [3].

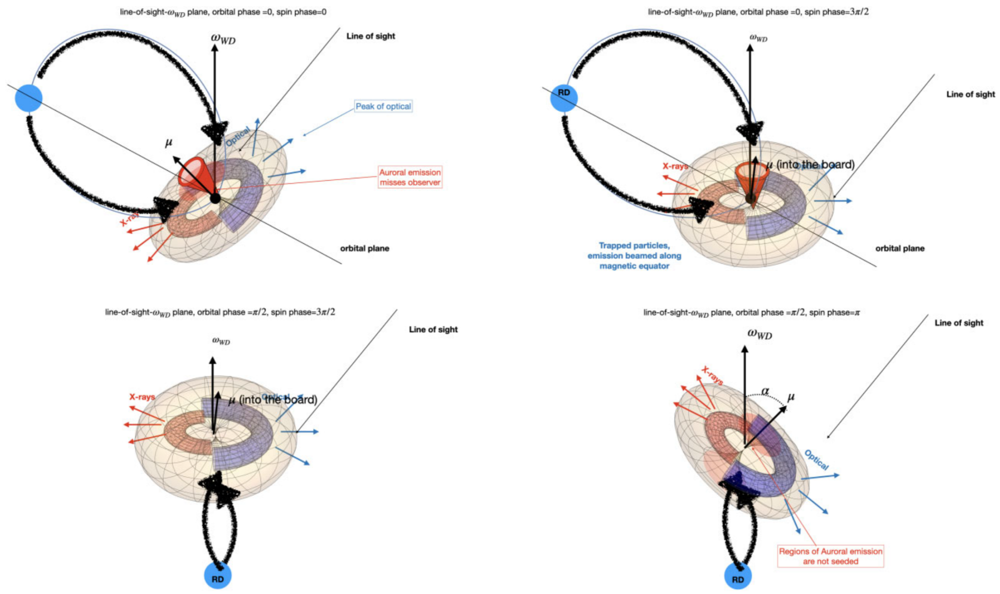

Figure 13. Examples of configurations at selected orbital and spin phases. The M-dwarf is represented by the blue circle and seeds particles towards the white dwarf, whose magnetic moment is represented by the red cone and visible only at certain spin phases as indicated. This geometrical model explains the observed behaviour of J1912 − 4410 based on the alignment of different emission regions with the line of sight.

Figure 1: Different configurations of the binary system from [4]

Below is a schematic of a theoretical model explaining the structure of the binary system

This target is the second known WD pulsar and is the only other discovered WD pulsar after the discovery of AR Sco. Analysing this target provides greater insight into the nature of WD pulsars while also providing key differences that expand the current understanding of magnetic CVs.

Data Analysis

Observations

The target was observed on two nights, namely 3 July 2021 (observation 1) and 4 July 2021 (observation 2). For observation 1, the duration of the observation lasted 69 minutes. For observation 2, the duration lasted 57 minutes. The data files provided for the target were `.txt` files which contained the time in Julian date and the brightness. This data was then supplemented into `Period04`, which is a software program designed to perform Fourier analysis of the time series data.

Below are the light curves of the time series data for each night

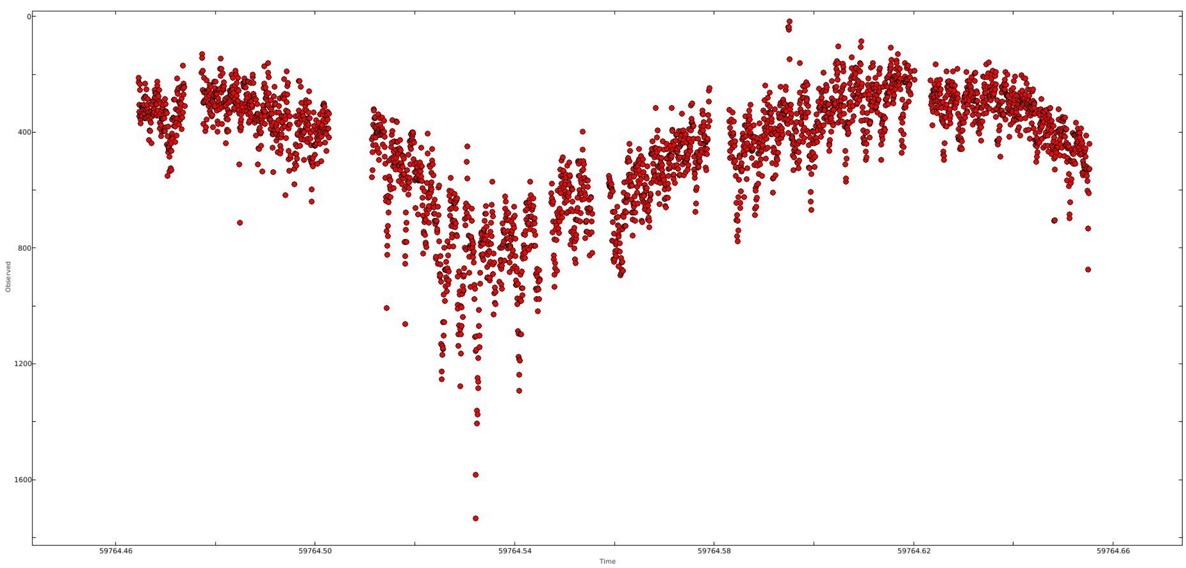

Figure 2: Observation 1 light curve

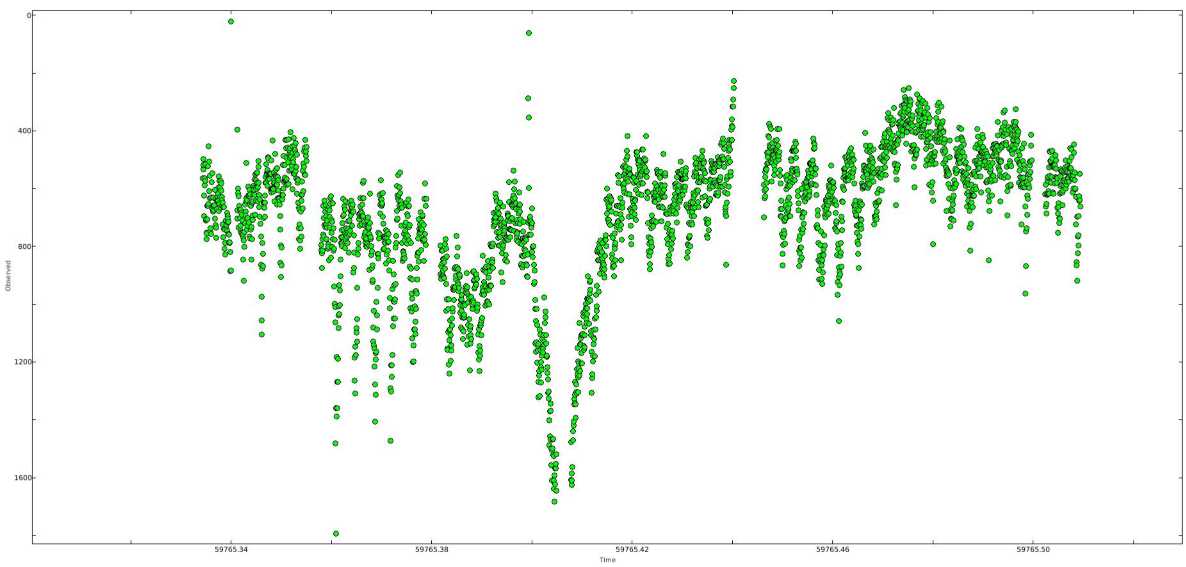

Figure 3: Observation 2 light curve

Observation 1 fig.2 shows a non-eclipsing binary system where some gaps in the data are due to the physical gaps between the CCD used during the observation. The pulse is observed to be single-peaked, indicating the bright component of the light curve is from the pole of the WD. Fourier analysis of the light curve reveals this in greater detail. The main through, though not a full eclipse, indicates that the pulses maybe coming from one pole of the WD such that when the system rotates, the bright pole moves away from the observer's line of sight. The modulation of the orbital cycle is smooth further showing the WD is not eclipsed by its companion.

Observation 2 fig.3 shows an eclipsing event and vary variable peaks. The eclipsing event being present during this observation but absent during the previous observation is likely due to the observation period being shorter than the orbital period. In this case, the M-dwarf would eclipse the WD as the bright pole spins across the observer's line of sight. The pulsations appear more sinusoidal during this observation compared to Observation 1 fig.2. The sinusoidal pulsations could be due to the observation of some accretion thread along magnetic field lines as the M-dwarf passes in front of the WD. This may have previously been out of the line of sight of the observer during Observation 1 fig.2; thus causing the change in the orbital modulation as another bright source is being observed.

Fourier Analysis

`Period04` was used to perform Fourier analysis of the time series data, where the frequencies of the light curve were calculated. To use the software, the given data in `.txt` format was uploaded to the program where the brightness and date columns were the only variables considered. The light curve plots (fig.2 and fig.3) were generated and the first Fourier transform was performed, using a discrete Fourier Transform algorithm, to generate a residuals plot. The Fourier analysis then made use of the residual data from the original data and generated frequencies from each iteration. The frequencies are stored as cycles per day, and the resulting wave is matched against the light curve to test how each frequency represents the data. After the initial Fourier analysis iteration, the orbital period was obtained. This is seen from the residual plot showing that after this initial frequency is subtracted, the light curves flatten out with some modulation at a shorter frequency indicative of another signal.

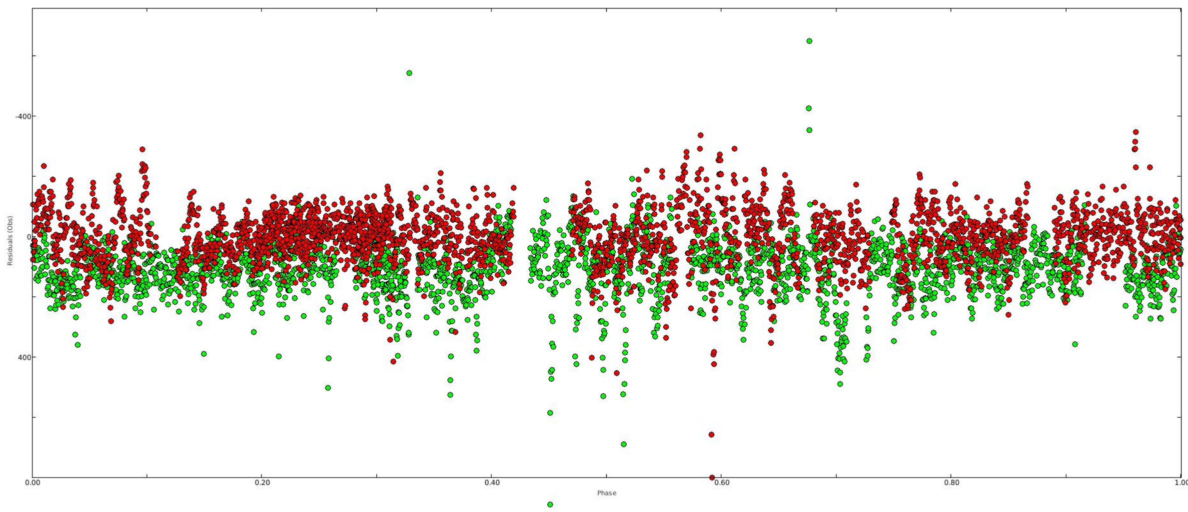

Figure 4: Phase diagram of the orbital frequency

From this plot fig.4, the light curve flattens out after the signal at 5.8638 cycles per day, which correlates to a period of ~ 4.09 hours. Below is the Fourier transform at this signal

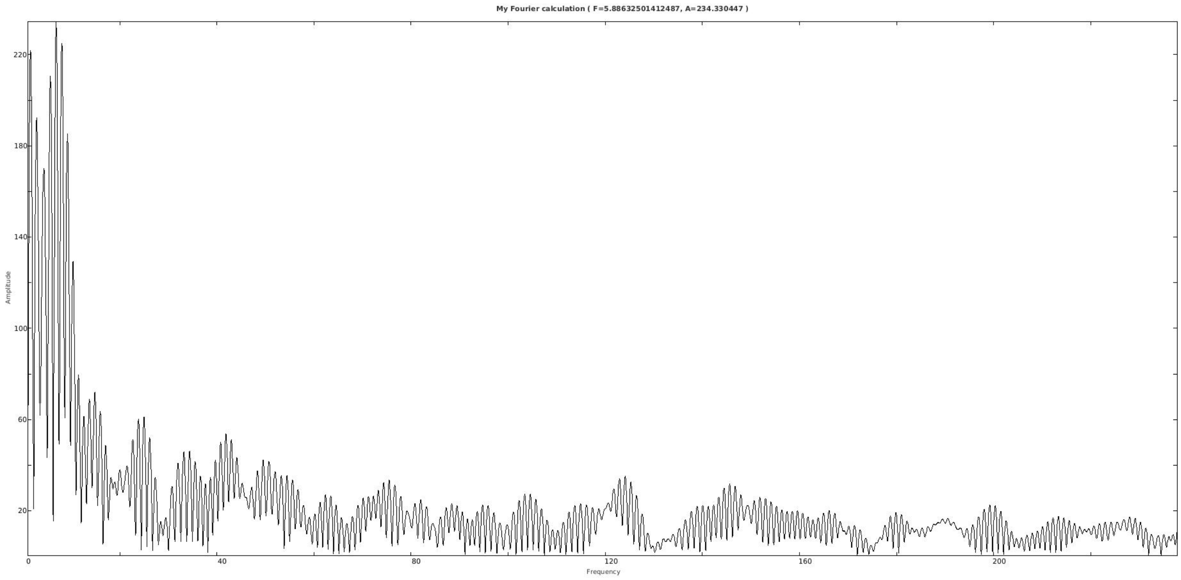

Figure 5: Fourier analysis around the orbital frequency

In the above plot, the $3^{rd}, 4^{th}$, and 5^{th} harmonics can be observed.

The second signal removed from the light curve had a frequency of 269.3216 cycles per day, which corresponds with a period of ~ 5.35 minutes.

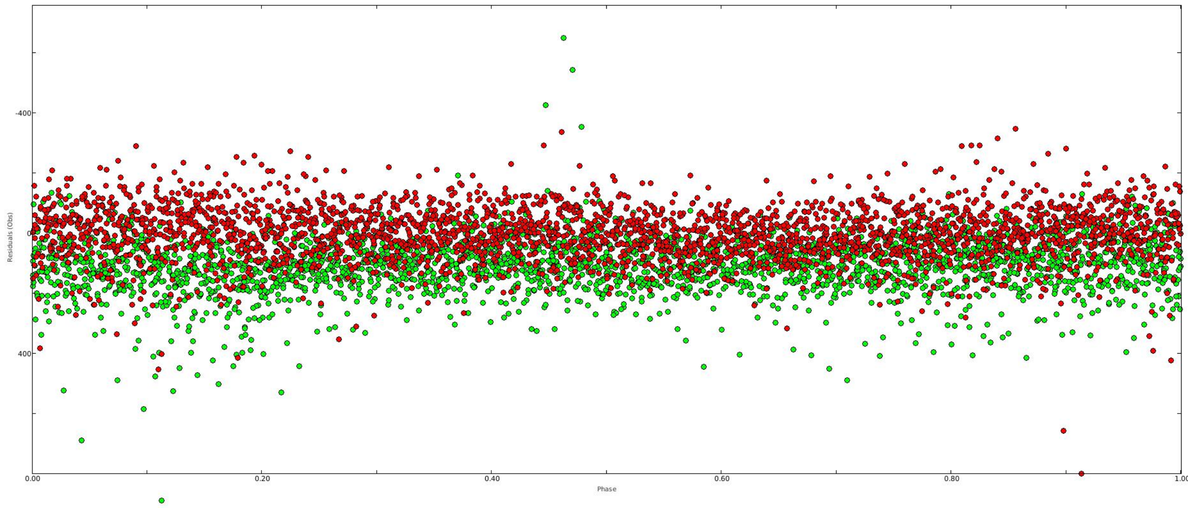

Figure 6: Phase diagram of the spin frequency

The above figure fig.6 shows that removing the above frequency removes the remaining residual data with some outliers due to the data having some errors. Below is the Fourier transform of the spin frequency

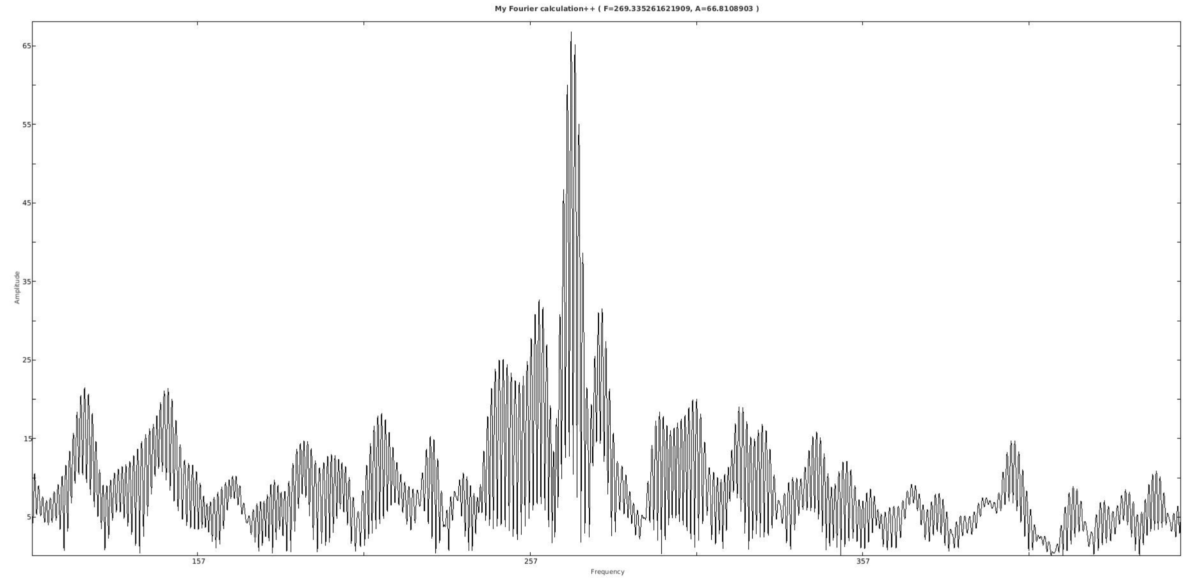

Figure 7: Fourier analysis around the spin frequency

The above plot fig.7 shows a strong signal occurring at 279.7718 cycles per day. This is potentially the observation of the bright threaded material that flows into the magnetic pole of the WD. The second harmonic is expected to occur at 538.6432269. Another signal was detected at 529.0379 which could be the expected second harmonic of the spin frequency, however this signal potentially corresponds to a beat period of 2.72 minutes. Upon inspection, the phase diagram of this signal does not indicate that removing this signal resulted in flatter residuals of the data. This implies the signal is possibly an alias.

Below are the light curves of the observations with the resultant Fourier waves

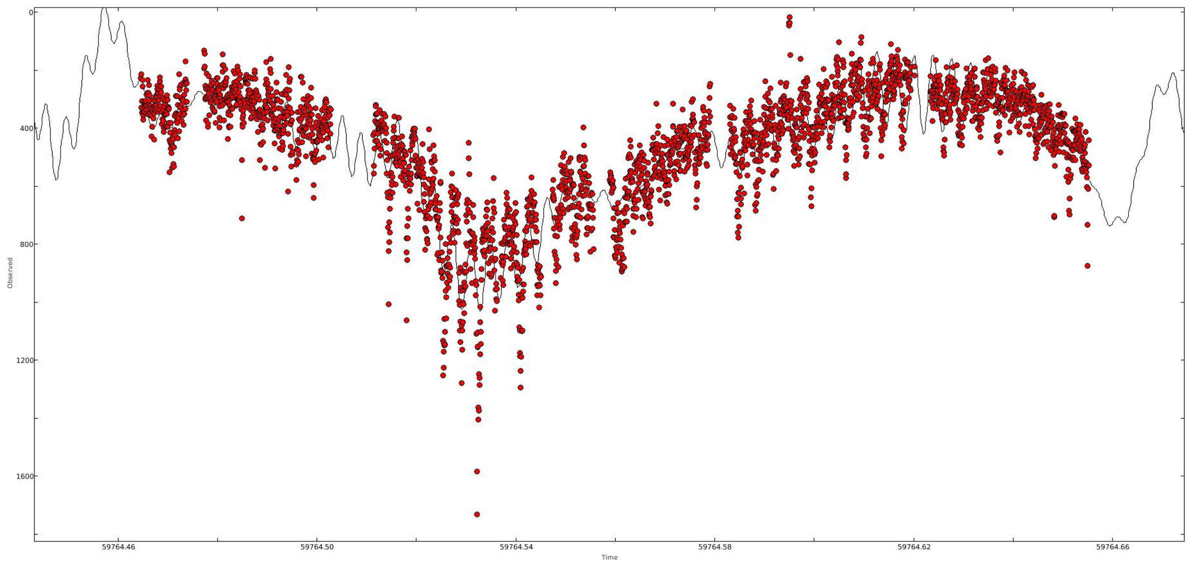

Figure 8: Observation 1 with Fourier analysis

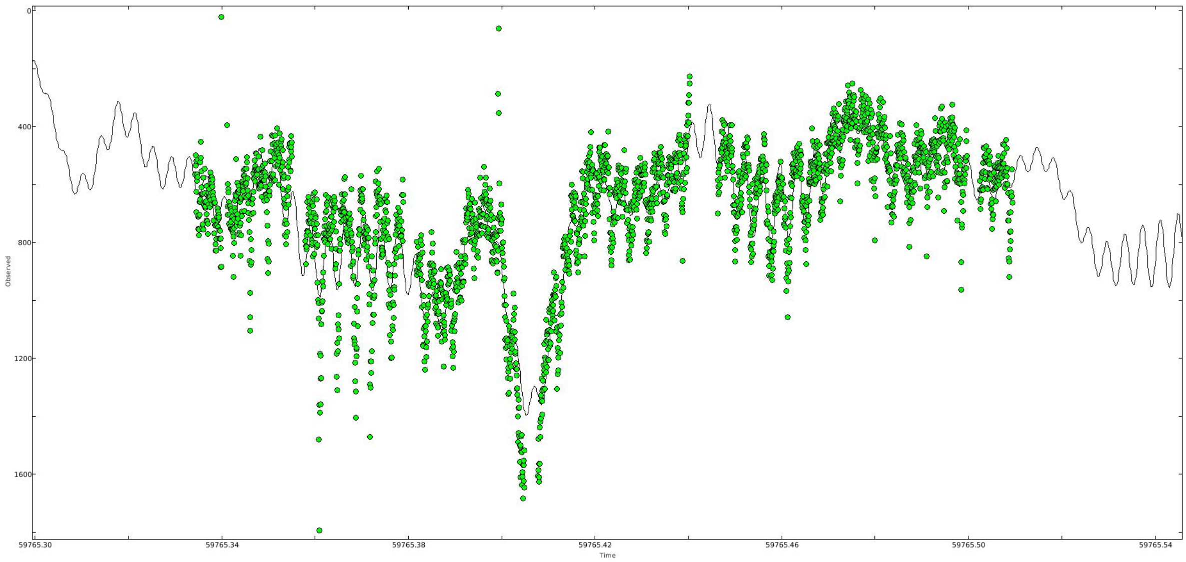

Figure 9: Observation 2 with Fourier analysis

The Fourier wave is averaged over both observations and works to reproduce the signal generated by the binary while also simulating what the signal would be between the observations. The accuracy of the wave can be improved with a longer observational period that records a full rotation of the system.

Discussion

Comparing the plots of the light curves with and without the Fourier analysis, it becomes clear that the binary system may be an eclipsing binary where the observations do not reach a full cycle due to the observation periods being less than the orbital period of the system. The Fourier analysis is able to accurately model the orbital period of the system and spin period of the WD pulsar. The measured orbital period of 4.09 hours has a 3.6 minute difference with the theoretical orbital period of 4.03 hours. The measured spin period of 5.35 minutes is accurate to 3 seconds of the theoretical spin period of the WD pulsar. The difference may be due to an incomplete phase coverage. the results validate the accuracy of the Fourier analysis conducted using `Peiod04`.

The empirical results match the theoretical expectation that the system contains a WD pulsar given the short spin period in comparison to the orbital period, baring many similairties to AR Sco which is a known WD pulsar. This is consistent with the X-ray and optical pulsations observed by Schwpoe(2023) [5], and Pelisoli (2023) [4] who observed UV and X-ray pulsations that peaked at prbital phase ~ 0.25. One lacking component in the empirical analysis is the beat period which has no theoretical value as this is not easily detected. Given that AR Sco has a pulse period of 1.97 minutes [4], the potentially alias detected signal in the data with a period of 2.72 minutes may be the beat period of the target system though further observations will be required given the lack of a complete orbital observation of the target.

A striking feature in the folded light curves is the difference in flux patterns between the two observation nights. The phase-resolved morphology suggests changing orbital aspect, possibly due to asymmetric emission from the accretion region or a rotating magnetic structure. Some articles use mass estimates which suggest the inclination of the system is 37° [5], while others hypothesise from the FUV observations that the inclination is $59 \pm 6°$ [4]. This indicates the received emission is not edge-on, which is favourable for the observation of the rotating pole. When the orbital phase is at ~ 0.5, the M-dwarf is out of the line of sight. In this configuration, the observer likely views the accreting magnetic pole of the white dwarf, which aligns with the hypothesis presented in Pelisoli (2023) [3] that some residual accretion may occur at the poles—even in the absence of a conventional accretion disk, which is consistent with the structure of a WD pulsar system. When the orbital phase is at ~ 1.0, the M-dwarf eclipses the WD, lowering the flux of the system and revealing significant flux modulation on timescales shorter than the orbital period but longer than the spin period of the WD pulsar. This may be attributed to the proposed accretion stream which would have a slower spin period than the WD pulsar.

The X-ray spectrum from the XMM-Newton observations [5] shows a dominant power-law distribution which is consistent with non-thermal emission, like synchrotron radiation of the accreting material, likely to occur at the poles. The low X-ray luminosity ($\sim 1.4 \times 10^{30}\ erg/s$) and lack of an accretion disk structure further suggest a low accretion rate polar system, where the WD's spin down might contribute a majority of the observed energy output.

HST COS observations obtained far-UV spectra of the WD pulsar in the system. The COS timetag data show very strong FUV pulsations that confirm the WD's spin period, and is able to detect a beat frequency between the orbital period of the system and the WD's spin period. This FUV detection of the beat period demonstrates that a component of the pulsed emission comes from reprocessing on the companion star as observed in AR Sco. In other words, the beat-frequency signal implies that the secondary's irradiated face reflects the rotating WD magnetosphere, producing an optical/UV pulse[4]. This observation is undetectable in the optical regime. The results from the Pelisoli (2023) [3] also reveal characteristics about the WD pulsar, namely the effective temperature being $T_{eff} = 11485 \pm 90K$ and the mass being approximately $M = 0.59 \pm 0.05 M_{\odot}$. This implies two scenarios of the WD. If the WD is in hydrostatic equilibrium then the core has not crystallised which implies that that crystallization-driven dynamos (thought to be a mechanism for generating the strong magnetic fields) are not the driving force behind the strong magnetic field in the core of WDs. The second scenario is the WD is not in hydrostatic equilibrium, such that accretion from the past has led to significant compressional heating. Which suggests that the WD may have spun up (due to accretion) before became magnetic. Furthermore, the lack of strong evidence indicating the WD has a strong magnetic field indicated the star is not purely pulsar-like (unlike AR Sco).

Conclusion

The analysis of J1912–44 confirms its classification as a white dwarf pulsar system similar to AR Sco, but with notable differences in physical and observational features. Time-series photometry and Fourier analysis accurately recovered the orbital period of 4.09 hours and spin period of 5.35 minutes, validating previous studies. The strong spin-modulated pulsations in X-ray and UV, along with X-ray flux peaking near orbital phase 0.25, suggest interactions between the white dwarf's magnetic pole and its companion star, likely involving accretion.

While no clear beat period was found in optical data, UV observations indicate a reflection off the companion, revealing that not all pulsed emissions originate directly from the white dwarf.

Theoretical analysis suggests either a non-crystallized core or one affected by past accretion, consistent with evidence of thermal imbalance in the white dwarf. Flux variability indicates complex orbital modulation, likely influenced by magnetic pole orientation and potential accretion threads, aligning with characteristics of low-accretion-rate polar systems.

Overall, J1912–44 is depicted as a white dwarf pulsar system driven by magnetospheric interactions and residual accretion. While it shares traits with AR Sco, its lower magnetic field and detectable UV beat period imply a more complex energy budget and evolutionary trajectory. Further monitoring and spectro-polarimetric studies are necessary to explore the relationship between spin-down, accretion, and magnetic field generation in these systems.

References

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[3] Ingrid Pelisoli et al. "A 5.3-min-period pulsing white dwarf in a binary detected from radio to X-rays". In: *Nature Astronomy* 7.8 (2023), pp. 931–942.

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