NY Lup (1RXSJ154814.5-452845) Analysis

MRTAID003

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1 Introduction

NY Lup, also identifiable as 1RXSJ154814.5-452845 or J15481459-4528399 [1], is magnetic cataclysmic variable (mCV), more specifically an intermediate polar (IP) with soft x-ray emission [2], located at a right ascension and declination of (237.060807°, -45.477782°) [3].

mCVs generally consists of two stellar bodies, that being a white dwarf with a strong magnetic field, and a companion star. In these systems, the companion star fills its Roche lobe and begins to accrete onto the white dwarf. However, unlike in other CVs, the formation of an accretion disc around the white dwarf is disrupted due to the strength of the white dwarf's magnetic field. Instead accretion occurs via streams onto small regions of the white dwarf. The difference between a polar and an intermediate polar comes down to the strength of the white dwarf's magnetic field; polars have stronger magnetic fields than those of intermediate polars.

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IPs with orbital periods of $\sim 6 - 10$ hours are rare (but not nonexistent) due to the IP period gap, where there is a sudden lack of IPs with orbital periods in the given range, but many found on either side of the range [4]. NY Lup is an interesting source, as it is intermediate polar with a long orbital period, specifically $P_\Omega = 9.87 \pm 0.03$ hours, as determined by de Martino et al. [5]. This places it right on the upper boundary of the IP period gap.

2 Data & Results

2.1 Observations & Photometry

Observations of NY Lup were taken on both the 25th and 26th of May 2009. Observations ran for approximately 8 hours 5 minutes on the May 25, and a further 8 hours 17.5 minutes on May 26, for a combined observation time of approximately 16 hours 22.5 minutes. The time between the two sets of observations is approximately 15 hours 28 minutes. The combined time series data for both days is plotted in Figure 1.

Figure 1 shows a clear difference in the amplitudes of the total counts from the first set of observations and the second. Observations from May 25th have significantly higher counts, at times more than an order of magnitude larger than observations from May 26th.

Given the significant differences in brightness between the two dates, the mean average of each data set was subtracted from the data, effectively normalizing the data such that the average of both data sets lie at zero. This makes the process of Fourier analysis easier as it removes the discrepancy between the brightnesses. The mean brightness subtracted counts time series data for both dates' observations are displayed in Figures 2 and 3.

These two plots show periodic variation in their counts, as well as variation in their overall shape. Figure 2 generally trends upward throughout, while Figure 3 trends upward to a point, then trends downward from a time (in Modified Julian Date) of roughly 54978.40. The periodic nature of the source is expected and could be the result of various factors, including the spin period of the white dwarf, and the binary orbital period, which will be discussed in Section 3.

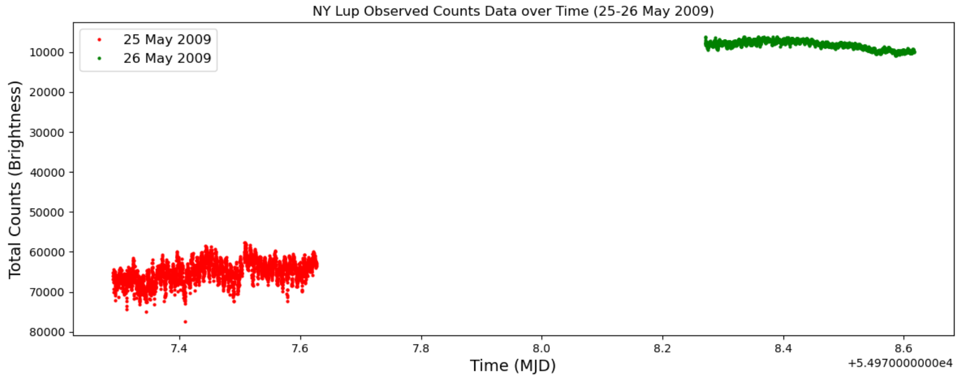

Figure 1: NY Lup Observed Counts Time Series Data for 25-26 May 2009. Observations from May 25 are shown in red, and observations from 26 May are shown in green.

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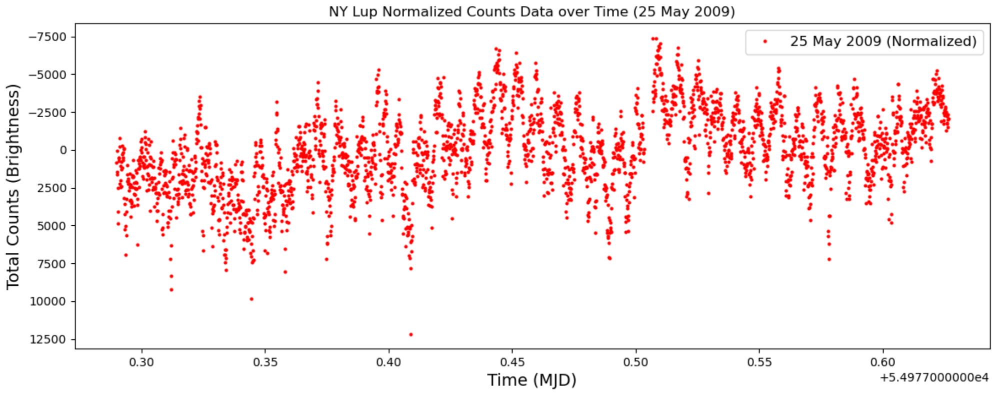

Figure 2: NY Lup Mean Brightness Subtracted Counts Time Series Data for 25 May 2009.

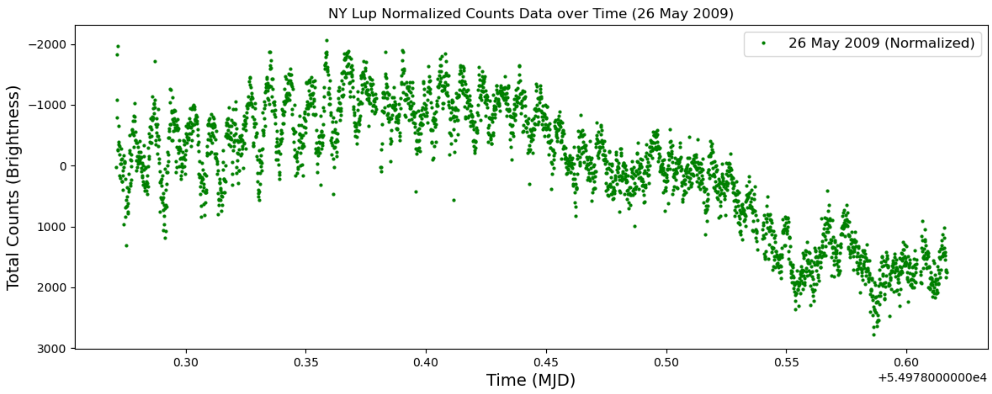

Figure 3: NY Lup Mean Brightness Subtracted Counts Time Series Data for 26 May 2009.

2.2 Fourier Analysis

By performing Fourier analysis, we can identify the dominant frequencies that arise from the data, which we can then analyze to learn about the various periods inherent in the system. For the base dominant frequencies, we search between the range of $0 - 3396.23$, the Nyquist frequency value, automatically calculated by Period04. The Nyquist frequency value is the maximum value before aliasing will occur [6]. It is therefore important that the base dominant frequencies are found below the Nyquist frequency, as it reduces the risk of identifying false frequencies that arise from aliasing.

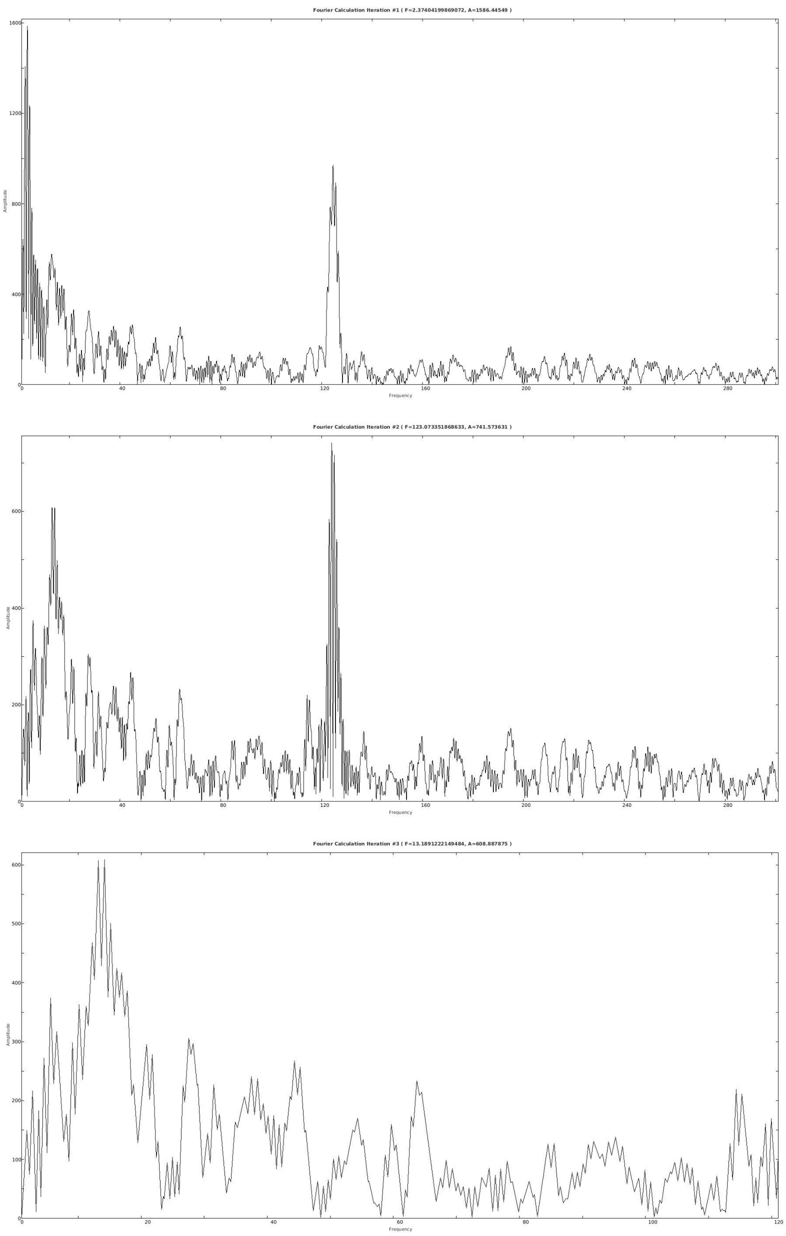

Figure 4: Frequency plotted against relative amplitude, used to identify dominant frequencies in the data. The top subplot shows a dominant frequency of $F = 2.37404199869072$ cycles/day with amplitude $A = 1586.44549$. The second subplot shows a new dominant frequency of $F = 123.073351868633$ cycles/day with amplitude $A = 741.573631$. The last subplot shows a third dominant frequency of $F = 13.1891222149484$ cycles/day with amplitude $A = 608.887875$.

Aliasing is an issue for the provided data, largely because of the gap in the dataset. Because the observations were not continuous and were comprised of two separate datasets, there is inherent uncertainty over the unobserved time. This is hard to combat, of course, given that observing continuously for extended periods of time require multiple telescopes around the world to work in conjunction with each other. This is not feasible most of the time, so daily gaps in the dataset are unavoidable.

Figure 4 consists of two subplots with frequency on the x-axis, and amplitude on the y-axis, and is used to find the dominant frequencies that can be found in the data. Dominant frequencies will be found in regions of greatest amplitudes, where the frequencies are at maximum.

In the first subplot, the maximum frequency clearly lies to the very left of the plot, near zero on the x-axis. This frequency is initially identified as $F = 2.37404199869072$ cycles/day with amplitude $A = 1586.44549$. Additionally, there is a clear secondary peak at a frequency just larger than 120 cycles/day. This frequency is identified as the new dominant frequency in the middle subplot, after the primary dominant frequency was removed. This second dominant frequency was identified as $F = 123.073351868633$ cycles/day with amplitude $A = 741.573631$. A third dominant frequency was identified in the lower subplot as $F = 13.1891222149484$ cycles/day with amplitude $A = 608.887875$, which can be seen as the secondary peak in the middle subplot.

So, after corrections of fit, from the Fourier analysis, three dominant frequencies were identified, specifically:

Frequency (cycles/day)	**Amplitude**	**Phase**	**Period (seconds)**
2.29725181431761	1635.10257	0.533125	37610.15638839088 (10.4472656634 hours)
123.608581563034	966.040447	0.822476	698.9805959057985
13.1810214193928	620.603878	0.789739	6554.87896203 (1.82079971167 hours)

Table 1: Dominant Frequencies and their corresponding Amplitude, Phase, and Period Values, identified by Fourier Analysis using the software Period04.

While the frequency, amplitude, and phase values displayed in Table 1 were automatically calculated by Period04, the period values were calculated manually using the following conversion equation:

$$\text{Period (seconds)} = \left[\frac{\text{Frequency (cycles/day)}}{60^2 \times 24}\right]^{-1}$$

The values in Table 1 for frequency and amplitude are notably different to the values quoted in the caption of Figure 4. The values in Figure 4 are uncorrected, taken directly from the data. The values in Table 1 are those values, but with the fits improved by Period04, which slightly alters the values.

Using the dominant frequencies listed in Table 1, phase diagrams can be constructed using each frequency, displayed in Figure 5. This plots the data as a function of phase through a cycle. If these dominant frequencies are real frequencies from the system, we expect to see a good correlation between the curves that form from the data from both days, and plot a polynomial fit to the data to help better visualize the shape of the overall curve. Data was normalized such that the maximum absolute value of the data was 1, so that the phase diagram curves created by the data sets from the separate days can be easier visualized.

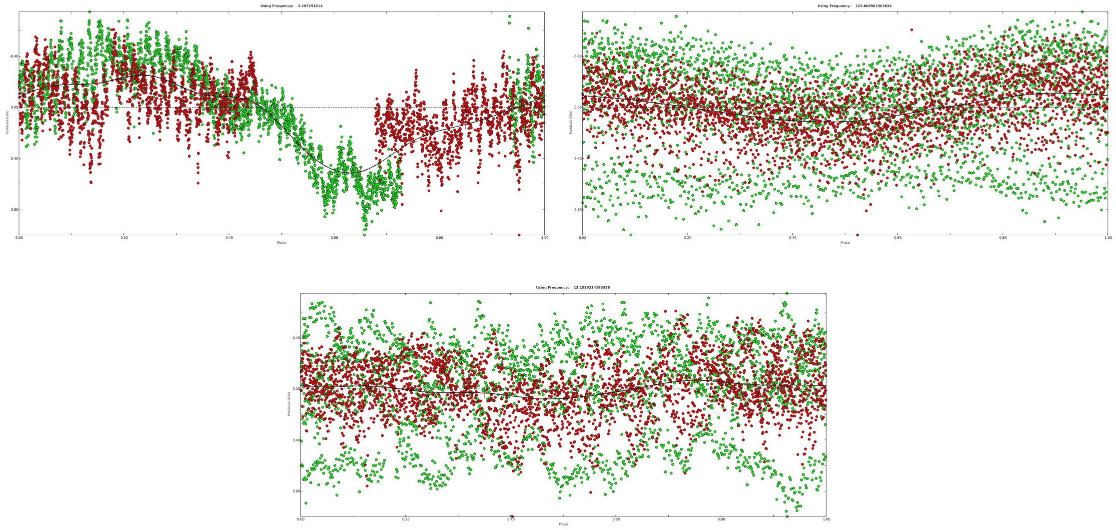

Figure 5: Phase Diagrams for the three identified dominant frequencies, with $F_1 = 2.297$ cycles/day in the top left, $F_2 = 123.609$ cycles/day in the top right, and $F = 13.181$ cycles/day at the bottom. The black line is a polynomial fit that uses a binning of 10. Data observed on 25 May 2009 is in red, while data observed on 26 May 2009 is in green.

Another way of confirming whether a dominant frequency is a real frequency from the system is to look at the frequency/amplitude profile in a zoomed in region around the frequency. Figure 6, 7, and 8 shows the zoomed in plots around frequency of 2.2297, 123.609, and 13.181 cycles/day respectively. If the identified dominant frequency is a fundamental frequency from the system, we expect to find the frequency at a local maximum peak in the plot. Additionally, the more harmonics that coincide with local minima/maxima, the more likely the frequency is from the system. Assuming the orbital frequency Ω and spin frequency of the white dwarf ω are correctly identified, we also expect that the beat frequency $(\omega - \Omega)$ coincides with a local maxima.

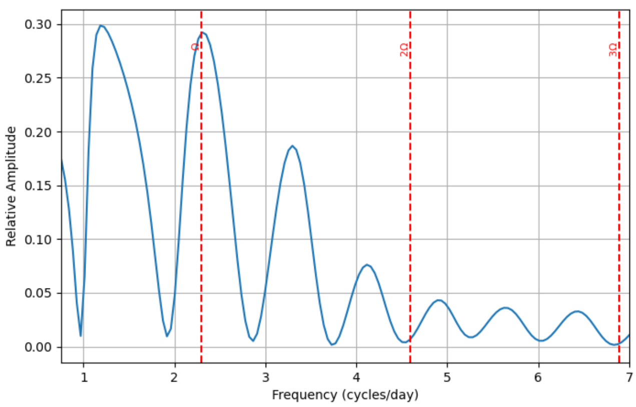

Figure 6: Frequency and Relative Amplitude plot, zoomed in to the region around dominant frequency 1, $F = 2.297$ cycles/day, indicated by the leftmost red dotted line, labeled Ω. Harmonics 2Ω and 3Ω are also displayed.

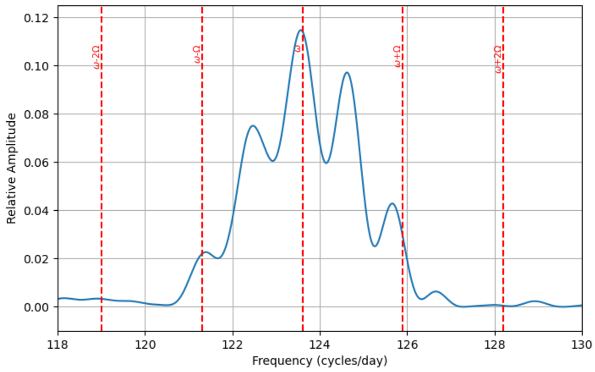

Figure 7: Frequency and Relative Amplitude plot, zoomed in to the region around dominant frequency 2, $F = 123.608$ cycles/day, indicated by the central red dotted line, labeled ω. Beat frequency $(\omega - \Omega)$ is plotted as well, along with some other combinations of ω and Ω: $(\omega - 2\Omega)$, $(\omega + \Omega)$, and $(\omega + 2\Omega)$.

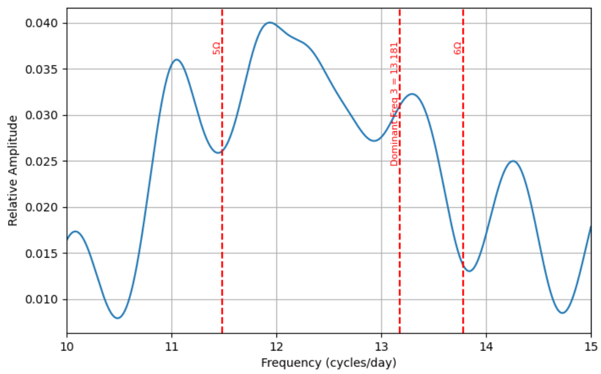

Figure 8: Frequency and Relative Amplitude plot, zoomed in to the region around dominant frequency 3, $F = 13.181$ cycles/day, indicated by the central red dotted line, labeled *Dominant Frequency 3*. Harmonics 5Ω and 6Ω are also displayed.

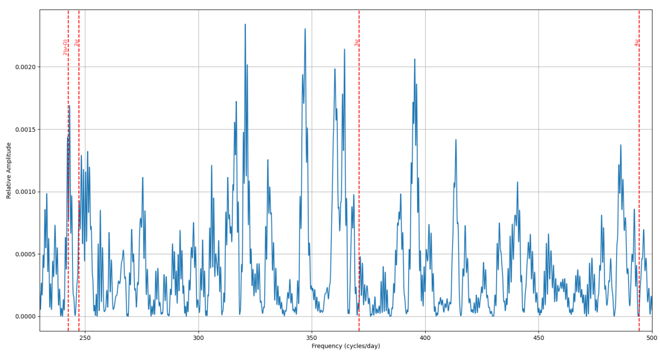

Figure 9: Frequency and Relative Amplitude plot, zoomed in to the region around the harmonics of the white dwarf spin frequency $\omega = 123.609$ cycles/day, specifically 2ω, 3ω, and 4ω. Double the beat frequency is also displayed, labeled $2(\omega - \Omega)$.

3 Discussion

3.1 Frequency 1: 2.297 cycles/day

The first dominant frequency corresponds to a period of ~ 37610.156 seconds, or ~ 10.447 hours, which is the longest period of the three identified dominant periods. Given that it is such a long period, especially when compared to the other two dominant periods, it is likely that this frequency is a result of the orbital period of the system, P_Ω.

The validity of the frequency as a fundamental frequency can be confirmed by looking at both the phase diagram using the frequency, as displayed in Figure 5 (top left), and a zoomed in frequency/amplitude plot around the frequency, shown in Figure 6. The phase diagram shows the curves from both days of observation (in red and green respectively) following a similar high order polynomial curve, which is well approximated by the black polynomial curve. The frequency/amplitude plot shows that the frequency, labeled Ω, lines up with a local maximum in the data. The harmonics of the frequency, labeled as 2Ω and 3Ω, also line up with the troughs in the plot. This adds further validity to the claim that this is a fundamental frequency of the system.

de Martino et al. determined that the binary orbital period was $P_\Omega = 9.87 \pm 0.03$ hours [5], which was later confirmed by Potter et al. [7]. This period is approximately 5.5% shorter than the period found in this report, which is notable, but there is clearly some correlation between the values. The difference between the frequency for the period calculated by de Martino et al. and the frequency of ~ 2.297 cycles/day is approximately 0.134 cycles/day. Errors introduced by the rounding of values, and the larger errors of the frequency ~ 2.297 introduced by Period04 could explain this difference.

The measurement of an orbital period of ~ 10.447 hours would place NY Lup firmly outside of the IP period gap, and not close to the border of the IP period gap as other papers like de Martino et al. have identified.

3.2 Frequency 2: 123.609 cycles/day

The second dominant frequency corresponds to a period of ~ 698.981 seconds, the shortest period of the three identified dominant periods. Given that it is the shortest period and lasts just longer than 11 minutes, it is unlikely that it relates to the binary orbital period of the system, as spin periods P_ω are usually smaller than the orbital periods P_Ω. It is more likely that this frequency relates to the rotation period of the system's white dwarf, P_ω.

In IPs, the white dwarf tends to adjusts its rotation period so that the magnetic field lines at the circularization radius travel at the same speed as the Keplerian orbit [8]. This means that in IP systems, the white dwarf usually has a high rotation period, which is in line with our assumptions.

As with the first dominant frequency, the validity of this second frequency as a fundamental frequency can be confirmed by looking at both the phase diagram using the frequency, as displayed in Figure 5 (top right), and a zoomed in frequency/amplitude plot around the frequency, shown in Figure 7. The phase diagram shows the curves from both days of observation (in red and green respectively).There is definite correlation visible between the observations for the separate days, and the black polynomial fit follows the stretched sinusoidal-like curve of the data. To confirm, we look at the frequency/amplitude plot. It shows that the frequency, labeled ω, coincides with a local maximum in the data. The expected beat frequency, $(\omega - \Omega)$ is plotted as well, assuming frequency $\Omega = 2.297$ cycles/day. This beat frequency coincides with another local maximum in the data. This adds further validity to the claim that this second frequency is a fundamental frequency of the system.

Haberl et al. first identified a dominant frequency of 693 seconds, and concluded that the related frequency is due to the white dwarf's rotation period [2]. This was later further constrained by de Martino et al., who identified a period of $P_\omega = 693.01 \pm 0.06$ seconds for the source [5]. This period corresponds to a frequency value of ~ 124.674 cycles/day. While this period is not exactly the same as the period of ~ 698.981 seconds that was identified, the frequency/period identified by de Martino et al. is within 0.87% of the value calculated for this report.

3.3 Equilibrium and Spin-to-Orbit Period Ratio

Given the calculated values: $P_\Omega = 37610.1564$ seconds and $P_\omega = 698.9806$ seconds, the ratio of P_ω/P_Ω for this system is:

$$P_\omega/P_\Omega = 0.0186$$

Typical values for the spin-to-orbit period ratio for the majority of IP is $P_\omega/P_\Omega = 0.10$. de Martino et al. notes that, given this very low value, and having found that the magnetic field strength of the white dwarf was lower than expected, this IP system is likely far from equilibrium. Additionally, this value corresponds to an asynchronous white dwarf [5].

3.4 Frequency 3: 13.181 cycles/day

The phase diagram that uses a frequency of 13.181 cycles/day (Figure 5 (bottom)) is the most incoherent, and seems that data from the two days are in anti-phase at points during the cycle, but it is difficult to say that definitively because of how difficult the curve is to visually comprehend.

It is likely that the frequency of 13.181 cycles/day is a result of aliasing, given that it is not the spin or orbital frequency, and does not appear to be a harmonic or combination of the spin and orbital frequencies. Looking at Figure 8, it is clear that this frequency does not coincide with the closest harmonic frequencies, namely 5Ω and 6Ω, and the frequency does not lie on a peak or trough. Looking at similar Figures 6 and 7 for dominant Frequency 1 (Ω) and 2 (ω) respectively, the points clearly coincide with local maxima in the data.

Additionally, this frequency is not mentioned in any of the papers referenced in this report. Therefore, we can disregard this frequency, as it does not seem to have much significance to the system.

3.5 Harmonics and Beat Frequency

As mentioned previously, the harmonics of the orbital frequency Ω, specifically harmonics 2Ω and 3Ω, are displayed in Figure 6. The harmonics 5Ω and 6Ω are plotted in Figure 8. All of these harmonics coincide with local minima in the plots. This provides validity the result of $\Omega = 2.297$ cycles/day.

Figure 9 shows the harmonics for the white dwarf spin frequency ω. The harmonic 2ω coincides with a local maximum, while the harmonics 3ω and 4ω coincide with local minima, as expected assuming that $\omega = 123.609$ cycles/day. These harmonics are not perfectly in agreement with the local maximum/minima, however, most likely a result of slight deviation from the true spin frequency value. But given that all three of these harmonics approximate the local maximum/minima that they are nearby means that it is likely the ω value is a good approximation of the true value.

The beat frequency is the difference between the two fundamental frequencies, the orbital frequency and the white dwarf spin frequency, written as:

$$\omega - \Omega \approx 123.609 - 2.297 = 121.312 \text{ cycles/day}$$

This corresponds to a beat period of 712.213 seconds. The beat frequency is plotted in Figure 7, and coincides with a local maximum in the frequency/amplitude plot, which help verifies the accuracy of the frequency. The beat frequency is an important frequency in IP systems, as it physically corresponds to the frequency at which the accretion onto the white dwarf switches from one of its magnetic poles to another [9].

A harmonic of the beat frequency appears in Figure 9, specifically double the beat frequency $2(\omega - \Omega)$. This coincides with a local minimum in the plot, solidifying our choice of orbital and spin frequencies.

4 Conclusion

Two fundamental frequencies were identified for NY Lup, namely the orbital frequency of $\Omega = 2.297$ cycles/day which relates to an orbital period of 10.447 hours, and a white dwarf spin frequency of 123.609 cycles/day which relates to a spin period of 698.98 seconds. A beat frequency of 121.312 cycles/day was found as a result, which corresponds to a period of 712.213 seconds.

The identification of NY Lup's orbital period as 10.447 hours would place it outside the IP period gap, and not on the gap's upper bound as was calculated in previous papers, such as by de Martino et al. who calculated a value of $P_\Omega = 9.87 \pm 0.03$ hours [5].

References

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