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Photometric Analysis and Classification of High Amplitude δ Scuti: AE Ursae Majoris

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ABSTRACT

AE UMa, a Population I high amplitude Delta Scuti (HADS), was observed for 4 nights through 14-21 March 2022. 454 Visual CMOS observations and 11 new times of maxima were obtained over a period of ~19.4 hours in total. Using python coding and Fourier analysis, a fundamental frequency $f_0 = 11.6251\ cd^{-1}$ was established and further observation of amplitudes of light maxima led to beat phenomenon period $P_b = 0.29360\ d$. Subsequently, the first overtone frequency $f_1 = 15.0316\ cd^{-1}$ was calculated and the period ratio $\frac{P_1}{P_0} = 0.7734$ was found to be relatively unchanged from Szeidl (1974). Thereafter, the period ratio-metallicity correlation determined by Hintz et al. (1997b) was used to estimate the metallicity [Fe/H] of AE UMa. I concluded that AE UMa is incorrectly classified as a Pop. II HADS (SX Phoenicis) and should be grouped with Pop. I HADS.

Introduction

Variable stars are stars that undergo changes in their Luminosity periodically. Over 100,000 have been identified, confirmed, and categorized into multiple groups based on their characteristics. The star Delta Scuti was first discovered to have a variable radial velocity by Wright (1900). Colacevich (1935) and Fath (1935) then reported variability in its light. Delta Scuti variables are now defined as short-period pulsators in the lower extension of the cepheid instability strip located close to or above the Main sequence evolutionary track. These stars are of spectral type late A to early F with a period ranging from 0.02d to 0.25d and amplitude variations close to or below 0.25 mag (Baglin et al., 1973; Breger, 2000; Aerts et al., 2010). Delta Scuti variables are the second most abundant variables in the Milky Way Galaxy after white dwarfs and can be used as standard candles to measure distance.

AE Ursae Majoris ($\alpha_{2000} = 09^h 36^m 53.0^s$, $\delta_{2000} = +44^\circ 01' 01.2''$) is one such variable star discovered by Geyer et al. (1955). Further studies by Tsesevich (1956) and Filatov (1960) were unable to classify it, but the spectral type was confirmed to be A9 by Götz & Wenzel (1961) and the type of variability as dwarf Cepheid by Tsesevich (1973). Amplitude variations in minima and maxima were observed and studied, and a beat phenomenon was observed by Szeidl (1974) and Broglia & Conconi (1975). AE UMa was then classified as SX Phoenicis (Garcia et al. 1995).

In this study, I will be performing accurate photometry of AE UMa to perform analysis on and provide evidence for two pulsations. I will also be discussing the credibility of the period ratio-metallicity correlation using stellar evolution aspects and its connection to AE UMa's classification.

Observations

Data Acquisition was performed for four nights, starting on March 14, 2021 and ending on March 21, 2021 (unforeseen and unfavourable conditions caused gaps in data). Visual observations of AE UMa were made using a 0.13m reflecting Newtonian telescope (focal length = 650mm) on an iOptron center-balanced equatorial mount. The telescope was equipped with a Canon EOS 60D DSLR, consisting of a CMOS sensor with 5184 x 3456 pixels and is APS-C (22.3 x 14.9 mm). This combination provides us with a field of view of $1^{\circ}58' \times 1^{\circ}19'$ and a plate scale of $1.36''\ px^{-1}$.

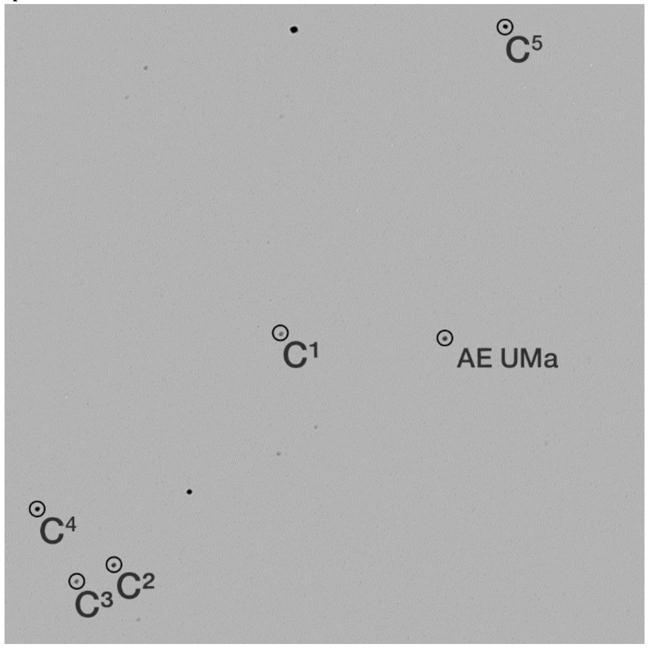

Figure 1. AE UMa star field with comparison stars labeled from C1 to C5. The field of view has been cropped for better perspective (28' x 28') with the north up and east left.

454 FITS image files were produced throughout ~19.4 hours, each of exposure time 145s. All images were calibrated using darks, biases, and flats, which were taken immediately after the acquisition to avoid over or under correction due to temperature differences and systematic errors specific to different nights.

Table 1. Points collected over the start and end Heliocentric Julian dates.

HJD (start)	HJD (end)	Date	Points
2459653.36	2459653.535	3-14-2022	95
2459654.422	2459654.62	3-15-2022	103
2459655.349	2459655.614	3-16-2022	144
2459659.395	2459659.601	3-21-2022	112

Methods

Data Reduction

For many variable star studies, the star's luminosity is calculated using its absolute visual magnitude, which is calculated using the apparent visual magnitude and the distance modulus.

Equation 1: Calculation of absolute visual magnitude and Luminosity

$$M = m - (5\ \log_{10}(d) - 5) \quad \text{and} \quad L_{*} = L_0 10^{-0.4M}$$

Where M is the absolute visual magnitude, m is the apparent visual magnitude, d is the distance to the star in parsecs, L_* is the star's luminosity, and L_0 is the zero-point luminosity.

However, the star's luminosity is irrelevant for this study, and we are only focused on the star's pulsation. Therefore, the FITS files were calibrated in AstroImageJ to increase the accuracy of our magnitude measurements ($\pm$13 mmag). After the calibration process, the images were plate-solved using ASTAP, which stored the centred right-ascension and declination of the current star field in the metadata of the FITS files and were then aligned in AstroImageJ. The final stack was then used to perform multi-aperture differential photometry. AIJ allows the input of apparent magnitudes of comparison stars, and so the differential magnitudes for AE UMa were calculated.

Equation 2: Calculation of apparent magnitude:

$$\text{Source\_AMag\_T1} = \frac{-\ln \sum_{xx} 2.512^{-\text{Source\_AMag\_Cxx}}}{\ln 2.512} - 2.5 \log \frac{\text{Source\_Sky\_Tnn}}{\sum_{xx} \text{Source\_Sky\_Cxx}}$$

where nn is the target aperture number, xx indexes comparison stars for which apparent magnitudes have been input, Source_AMag_Cxx is the apparent magnitude input, Source_Sky_Tnn and Source_Sky_Cxx are net integrated counts in apertures nn and xx. Using multiple comparison stars helps reduce errors caused by atmospheric disturbances (Collins et al., 2017).

Table 2. Comparison stars used during the aperture photometry of AE Uma and their respective Visual apparent magnitudes.

Label	Star Name	α_{2000}	δ_{2000}	V (mag)
C1	TYC 2998-1249-1	$09^h37^m28.6^s$	$+44^\circ01'16.8''$	11.32
C2	TYC 2998-1615-1	$09^h37^m41.2^s$	$+43^\circ49'26.9''$	10.75
C3	TYC 2998-1456-1	$09^h37^m47.4^s$	$+43^\circ48'10.4''$	11.32
C4	TYC 2998-1374-1	$09^h38^m03.0^s$	$+44^\circ50'14.1''$	10.67
C5	TYC 2998-338-1	$09^h37^m11.1^s$	$+44^\circ17'01.5''$	10.51

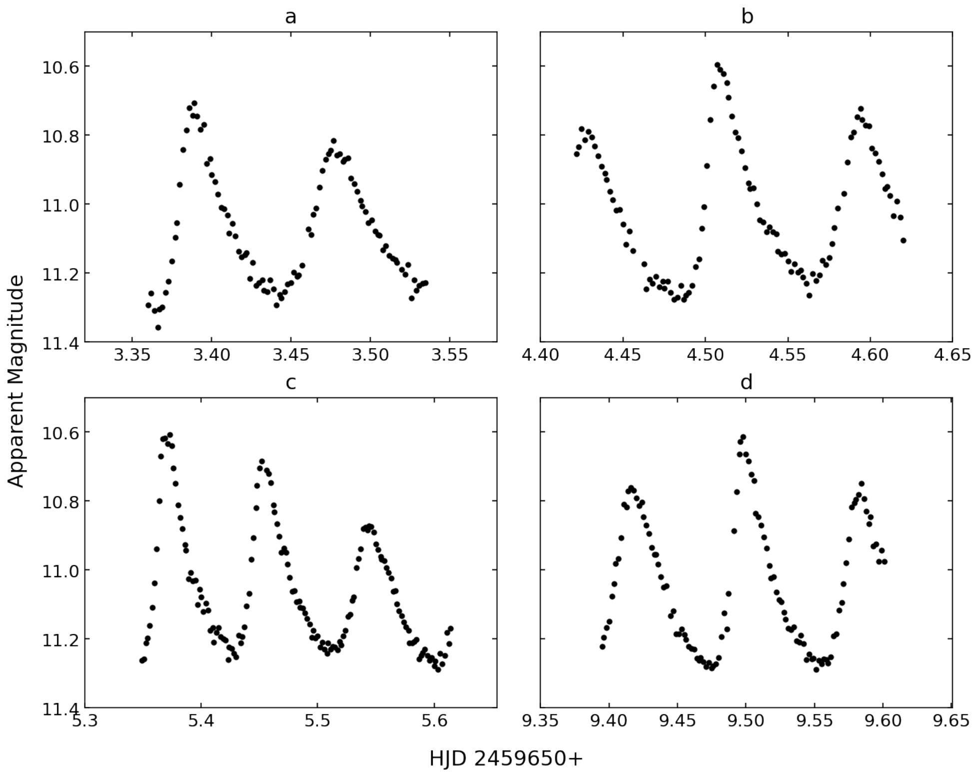

Figure 2. Light curves were created using the differential magnitudes calculated and HJD for each measurement.

Data Analysis

Frequencies and time periods of pulsations of variables can be calculated using numerous methods. However, the data collected is not continuous; therefore, Discrete or Fast Fourier Transforms will not work, so I have chosen the astropy Lomb-Scargle Periodogram package (Lomb, 1976; Scargle, 1982; Prince-Whelan et al., 2018; Robitaille et al., 2013). The Lomb-Scargle periodogram uses least-square algorithms for sinusoidal curves to determine the best fit and frequencies/time periods.

The fourier analysis returns a fundamental frequency of f_0 = 11.625611 ± 0.000001 cd^{-1} and a period of $P_0 = 0.08601698 \pm 0.0000002\ d$

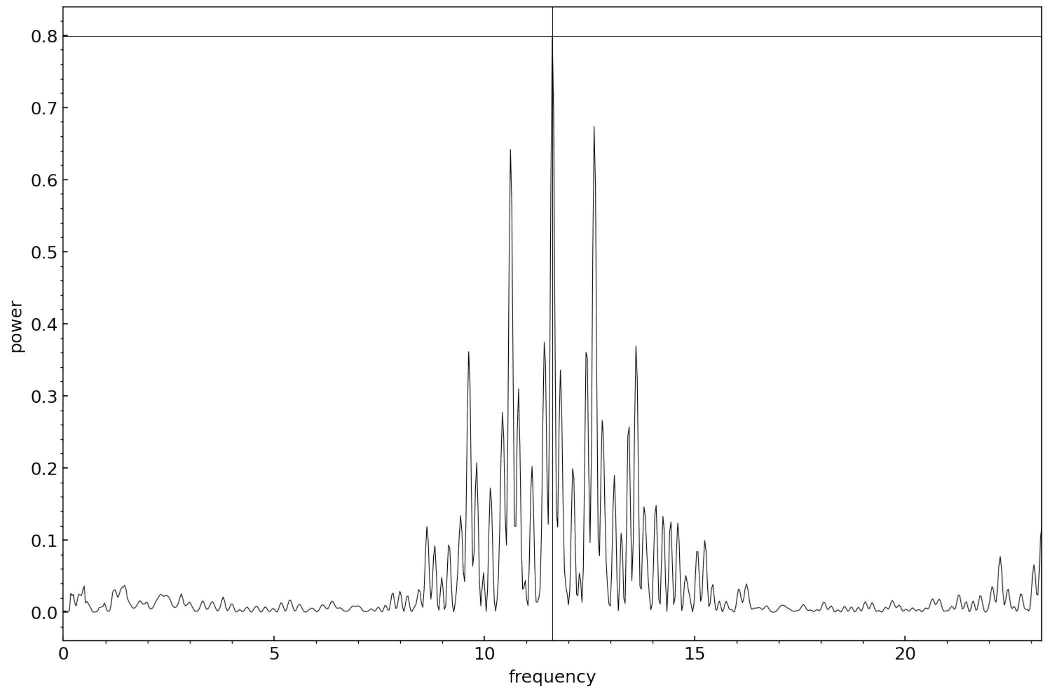

Figure 3. Periodogram of the time-series data with the strongest frequency represented by a vertical line.

Equation 3: The ephemeris for times of maxima:

$$\mathrm{HJD}_{max} = 2459653.389 + 0.08601698\,E$$

This ephemeris and time-period are consistent with Niu et al. (2017) within $\pm$ 0.0000002 days, although it does not account for the changing time-period (Coates & Landes, 2008) and will incur offsets in the future.

Table 3. Using the ephemeris, times of maxima and the apparent magnitude at the time were found, a total of 11 maxima were observed.

Times (HJD)	Apparent Magnitude	Cycle (E)
2459653.389	10.706	0
2459653.479	10.858	1
2459654.431	10.806	12
2459654.511	10.622	13
2459654.595	10.755	14
2459655.371	10.633	23
2459655.456	10.710	24
2459655.544	10.871	25
2459659.418	10.770	70
2459659.500	10.663	71
2459659.584	10.750	72

Given the bi-periodicity of AE UMa a first overtone is present which causes the variation in apparent magnitude throughout the fundamental pulsation, however, the fundamental pulsation's amplitude is much larger so times of maxima are dependent on its frequency. Interference between these two pulsations causes a beat phenomenon which is most prominent at maxima and so times of maxima and apparent magnitude were put through a fourier analysis. This beat phenomenon is of frequency $f_b = 3.405972 \pm 0.0002$ cd^{-1} and period $P_b = 0.29360189 \pm 0.00004$ d.

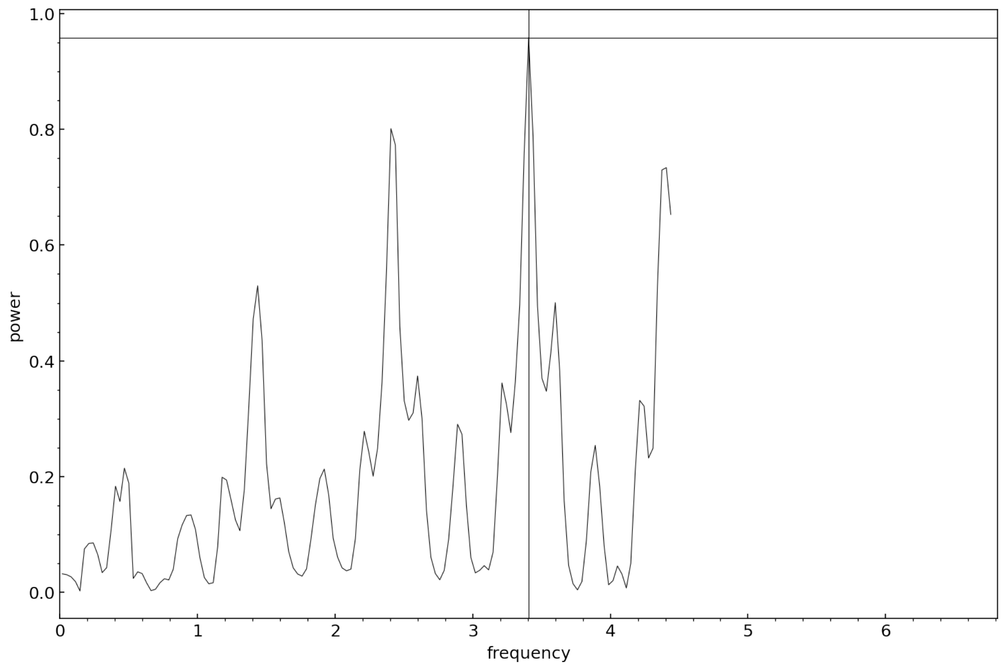

Figure 4. Periodogram of amplitude variations with the strongest frequency represented by a vertical line.

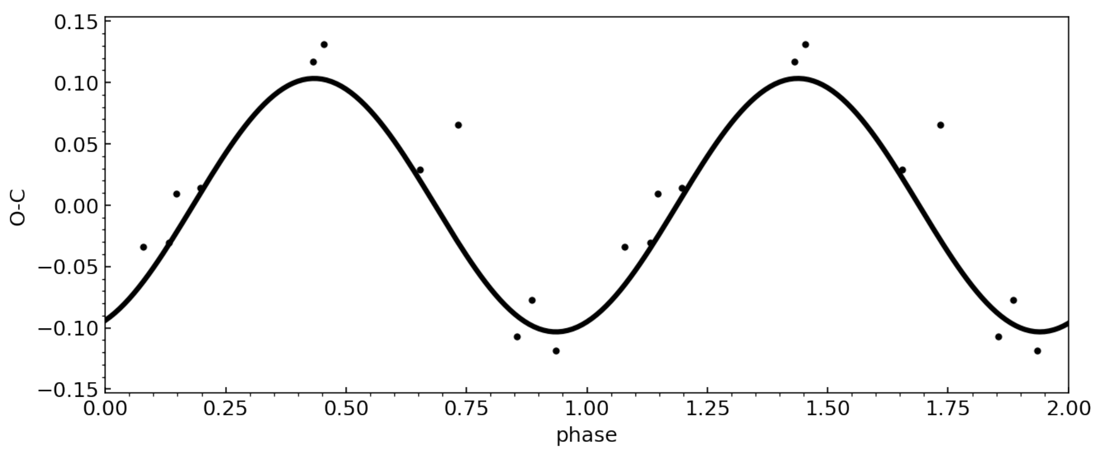

Figure 5. The (O-C) phase fold of the beat phenomenon with a sinusoidal fit over a beat phase.

Equation 4: Interference of the first overtone and fundamental frequencies:

$$f_b = f_1 - f_0$$

Equation 5: the first overtone frequency follows as this relation:

$$\frac{1}{P_1} = \frac{1}{P_0} + \frac{1}{P_b} \quad \text{or} \quad f_1 = f_0 + f_b$$

From equation five, we find the first overtone frequency $f_1 = 15.031584 \pm 0.0001$ cd^{-1} and period $P_1 = 0.06652659 \pm 0.0000005$ d. Using the fundamental frequency and first overtone we are able to model AE UMa's pulsation and amplitude perfectly.

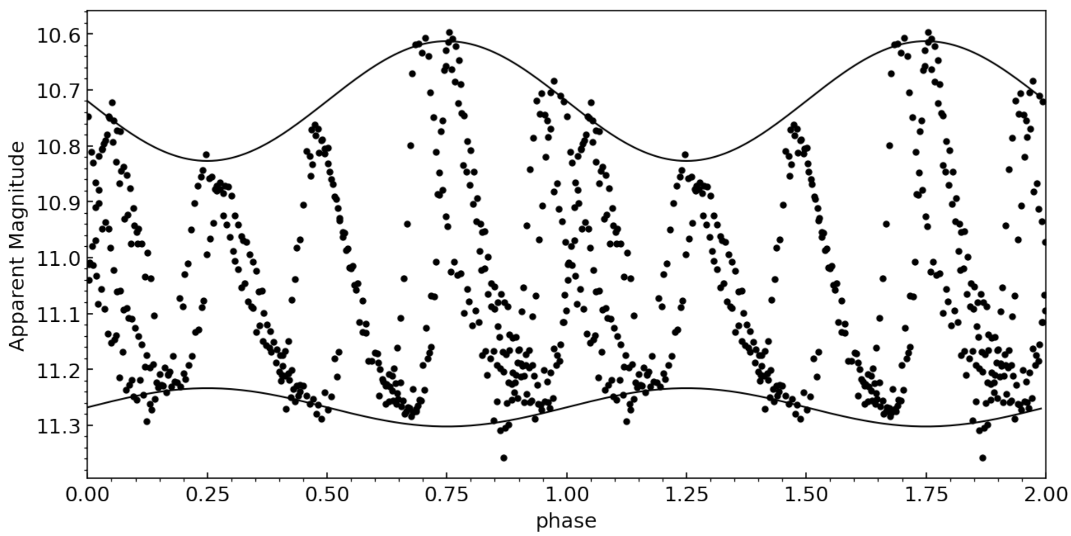

Figure 6. The magnitudes at minima and maxima are plotted against a beat period phase. A phase difference of $\frac{P_b}{2}$ is observed between minima and maxima pulsations.

Results

Equation 6: The period-ratio:

$$\frac{P_1}{P_0} \quad \text{or} \quad \frac{\text{First Overtone Period}}{\text{Fundamental Period}}$$

The period-ratio for AE UMa derived from my data is $\frac{P_1}{P_0} = 0.7734$.

A post-main-sequence star is expected to undergo evolutionary changes. Of these changes, a changing radius will affect the star's pulsation periods in that they change at an equal rate and in the same direction. Based on previous research AE UMa's fundamental period has been increasing (Niu et al., 2017); however, its first overtone period is decreasing at a different rate (Zhou, 2001). This is unusual given that AE UMa has left the Main-Sequence and should be undergoing evolutionary changes (Niu et al., 2013).

Cox (2017) states that the fundamental pulsation originates mainly from the star's interior compared to the first overtone, which stems closer to the exterior. Moreover, since the evolutionary effect results from changes in the nuclear reaction in the star's core, which then disperses outwards over time, we can say that the exterior of a star experiences evolutionary changes later than the interior. This can explain the different directions and rate of change of the pulsations.

It is known that the metallicity of a star increases as it crosses the main sequence. Hydrogen and Helium get depleted, and the core is forced to produce heavier elements through fusion. This directly correlates with the change in pulsations and the metallicity, which was put into a linear regression by Hintz et al. (1997b).

Equation 7: The linear period ratio-[Fe/H] correlation:

$$\frac{P_1}{P_0} = -0.0044\left[\frac{Fe}{H}\right] + 0.7726$$

Where $\frac{P_1}{P_0}$ represents the period ratio and [Fe/H] is the metallicity, it is evident that the period ratio decreases with increasing metallicity. Inputting our period-ratio of $\frac{P_1}{P_0}$ = 0.7734 we get a metallicity of [Fe/H] ≈ -0.2 which agrees with multiple historical values.

Table 4. Observed and calculated metallicities from various studies of AE UMa.

[Fe/H]	Observer
-0.3	Rodriguez et al. (1992)
-0.1 to -0.4	Hintz et al. (1997a)
-0.32	Niu et al. (2017)
-0.2	This study

Hence, this proves the linear regression model and the theory that the exterior is subject to changes later than the interior. The first overtone period is decreasing while the fundamental period has been increasing, which will lead to the period ratio decreasing as the star evolves and its metallicity increases.

Discussion

SX Phoenicis stars are known to be metal-poor stars and given the metallicity [Fe/H] = 0.7734, period-ratio $\frac{P_1}{P_0}$ = 0.7734, and my deduction of AE UMa being a post-main-sequence star, I conclude that AE UMa should not be classified as a Population II HADS (SX Phoenicis) rather it should be a Population I HADS. This conclusion will help future research use AE UMa as a much more effective standard candle and explain trends between changes in pulsation periods and the evolution of bimodal variables.

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