On the Light Curves of AM CVn

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ABSTRACT

Light curves of AM CVn are analyzed by decomposing them into their Fourier components. The amplitudes of the fundamental mode and overtones of the three components: the superhumps, the negative superhumps and the orbital variations, are found to be variable. This implies that variations in the shape of the observed light curve of AM CVn are not only due to the interference between those components, but also due to the variability of their parameters.

Key words: binaries: cataclysmic variables, stars: individual: AM CVn

1. Introduction

AM CVn is a prototype of the ultra short period, helium cataclysmic binaries (Nelemans 2005, Kotko et al. 2012). Its light variations, discovered in 1962 (Smak 1967), are so complicated that it took many decades and several, extensive photometric and spectroscopic studies (Patterson et al. 1993, Harvey et al. 1998, Skillman et al. 1999, Nelemans et al. 2001, Roelofs et al. 2006 and references therein) before they were fully interpreted and the basic binary system parameters well established.

Thanks to those investigations the light variations of AM CVn are now known to be a superposition of three components: the superhumps with $P_{SH} = 1051.2s$, the negative superhumps with $P_{nSH} = 1011.4s$, and variations with the orbital period $P_{orb} = 1028.7s$. The superhumps are the dominant component and their period is the main observed period. In view of this it could be added that light variations of AM CVn, when discovered in 1962, were the first – unrecognized at that time(!) – example of superhumps.

There are still problems requiring further attention, such as the superhump period variations (cf. Fig.2 in Skillman et al. 1999), or problems related to the fact
that the observed light curve has the shape of a distorted double sine-wave, dominated by the strong first overtone 525s signal, which is the peculiar property of AM CVn.

Another problem is related to large variations in the shape of the light curve, observed on shorter time scales. The aim of the present paper is to clarify this point by decomposing representative light curves of AM CVn into their Fourier components.

2. The Seasonal Mean Light Curves

Skillman et al. (1999) collected and analyzed long series of photometric observations of AM CVn which allowed them to determine the seasonal mean superhump (SH), orbital (orb) and negative superhump (nSH) light curves observed in the years: 1978, 1997 and 1998 (Skillman et al. 1999, Figs 5 and 6).

Those light are decomposed into their fundamental mode and the first three overtones

\[ m = \langle m \rangle + \sum_{k=0}^{3} A_k \cos[2\pi (k+1) (\phi - \phi_{k,\text{min}})], \]

(1)

where \( k = 0 \) corresponds to the fundamental mode, while \( k = 1, 2, 3 \) – to the overtones. The resulting values of the amplitudes and phases of minimum are listed in Table 1; their formal errors are quite small: \( \sigma_A \sim 0.3 - 0.6 \text{mmag} \) and \( \sigma_\phi \sim 0.01 - 0.03 \).

An important comment must be made here in order to avoid confusion and possible misunderstandings. In the case of the overtones the phases of minima can be defined in two different ways: either by refering them to the main period \( P \), or to the overtone period: \( P_k = P/(k+1) \). The resulting fundamental mode phases \( \phi_{\text{min}}^f \) and the overtone phases \( \phi_{\text{min}}^{ovt} \) are related by

\[ \phi_{\text{min}}^f = \frac{\phi_{\text{min}}^{ovt}}{(k+1)}. \]

(2)

The phases defined by Eq.(1) and listed in Table 1 are – obviously – the fundamental mode phases.

Returning to Table 1 few facts can be noted with respect to the superhump component: (1) The amplitudes and phases of minima of the overtones do not change significantly from season to season; this explains the stability of the light curve over longer time scales. (2) The amplitude of the fundamental mode is very low, but not negligible, while its phase of minimum is probably variable. (3) The phase of minimum of the dominant first overtone differs from 0 and it is due to the contributions from the second and third overtones that in the observed curve it is shifted to 0.

\[ ^{1} \text{It must be noted here that Eq.(1) in Smak (2016) was – regretfully – misprinted. Its correct form, used in the analysis, was identical with Eq.(1) given above.} \]
### Table 1
Fourier Components of the Seasonal Mean and 1974 Light Curves

| A(mmag) | \( A_0 \) | \( A_1 \) | \( A_2 \) | \( A_3 \) |
|---------|---------|---------|---------|---------|
| SH <1978> | 1.7 | 10.6 | 2.5 | 0.8 |
| <1997> | 2.3 | 9.7 | 3.3 | 0.9 |
| <1998> | 3.0 | 11.8 | 3.0 | 1.4 |
| 1974 | 7.5 | 11.5 | 1.6 | 3.5 |
| orb <1997> | 4.1 | 1.6 | 0.4 | 0.4 |
| <1998> | 4.0 | 2.7 | 0.2 | 0.6 |
| 1974 | 2.8 | 8.2 | 4.8 | 0.6 |
| nSH <1978> | 6.3 | 0.6 | 0.6 | 0.3 |
| <1998> | 9.0 | 0.4 | 0.5 | 0.4 |
| 1974 | 5.8 | 4.4 | 1.6 | 0.6 |

| Phases | \( \phi_{0,min} \) | \( \phi_{1,min} \) | \( \phi_{2,min} \) | \( \phi_{3,min} \) |
|---------|---------|---------|---------|---------|
| SH <1978> | -0.15 | +0.03 | -0.04 | -0.04 |
| <1997> | -0.31 | +0.04 | -0.02 | +0.02 |
| <1998> | -0.25 | +0.04 | -0.04 | -0.02 |
| 1974 | -0.04 | +0.02 | +0.03 | -0.03 |
| orb <1997> | -0.04 | 0.00 | +0.10 | -0.11 |
| <1998> | -0.03 | +0.02 | -0.06 | +0.09 |
| 1974 | +0.01 | +0.02 | -0.05 | +0.07 |
| nSH <1978> | -0.01 | +0.17 | +0.06 | -0.05 |
| <1998> | 0.00 | +0.12 | -0.12 | -0.06 |
| 1974 | +0.02 | +0.02 | -0.11 | -0.09 |
3. The 1974 Light Curves

3.1. The Light Curves

In order to study the evolution of the light curve of AM CVn on a short time scale we analyze the light curves observed on two nights in January 1974 (Smak 1975, Figs 1 and 2). They are shown in the left panels of Figs 1 and 2. Each curve is based on three 1051s cycles (i.e. $3P_{SH}$) and each next curve is shifted with respect to the previous one by $1.5P_{SH}$. The phases are defined by the following local elements

$$\text{Pri.Min.} = JDhel 2442071.81746 + 0.01216667 \times E.$$  

First of all we note that the behavior of AM CVn on those two nights was different. On the first night (Fig.1) the light curve was of the "standard" shape and only at the end of the run the depth of the secondary minimum started to decrease. On the second night (Fig.2) all light curves were peculiar with the mean light curve (not shown here) showing only the first minimum and the first maximum.

It is obvious that the changes of the observed light curve which occur on a short time scale are due to the interference between its three components: the superhumps, the negative superhumps and the orbital variations. To describe their contributions one would have to determine – for each of them – the amplitudes and phases of minimum of each of the four Fourier components, altogether then: $3 \times 4 \times 2 = 24$ free parameters. This is obviously impossible. The only way to improve the situation is to begin with the Fourier analysis of the observed light curves.

3.2. The Fourier Analysis

All light curves shown in the left panels of Figs.1 and 2 were decomposed into their fundamental mode and the first three overtones. The results are shown in the right panels of those figures, where the resulting amplitudes and phases of minima are plotted as a function of time.

All parameters show considerable variations. The only exception are the phases of minimum of the first overtone which are practically constant and equal to those obtained from the mean seasonal superhump light curves. This illustrates the stability of the main 525s signal.

3.3. The Solution

Each of the Fourier components can be represented in the form

$$\Delta m_k = A_k^{SH} \cos \phi_k^{SH} + A_k^{orb} \cos \phi_k^{orb} + A_k^{nSH} \cos \phi_k^{nSH},$$

which involves six free parameters: the three amplitudes and three zero-points of overtone phases. In what follows we assume that those parameters remained constant during two nights.
Since the light curves were based on time intervals $\Delta t = 3P_{SH} = 0.0365$ d which are short compared to the two beat periods: $P_{orb/SH} = 0.5571$ d and $P_{nSH/SH} = 0.3092$ d we can replace $\phi_k^{orb}$ and $\phi_k^{nSH}$ in Eq.(4) with $\phi_k^{SH}$ and two, practically constant beat phases: $\phi_k^{orb} = \phi_k^{SH} + \phi_k^{orb/SH} \quad$ and $\phi_k^{nSH} = \phi_k^{SH} + \phi_k^{nSH/SH}$.

The resulting expression for $\Delta m_k$ depends now only on $\phi_k^{SH}$ and the phase of minimum $\phi_k^{SH,min}$ can be obtained from the condition

$$d\Delta m_k / d\phi_k^{SH} = 0,$$

(5)

while the observed amplitude of the light curve is
Fig. 2. Analysis of light curves of AM CVn observed on January 24/25, 1974. See caption to Fig.1.

\[ A_{k,obs} = \Delta m_k(\phi_{k,\text{min}}^{SH}). \]  (6)

Recalling that the phases of minimum \( \phi_{k,\text{min}} \), determined in Section 3.2 from the Fourier analysis using Eq.(1), refer to the fundamental mode we must convert the overtone phases of minimum also to the fundamental mode phases by using Eq.(2).

Finally, we determine the six unknown parameters, i.e. \( A_k^{SH} \), \( A_k^{orb} \), \( A_k^{nSH} \), and \( \phi_{k,\text{min}}^{SH} \), \( \phi_{k,\text{min}}^{orb} \), \( \phi_{k,\text{min}}^{nSH} \), by fitting – via the least squares solution – the amplitudes and phases of minimum, obtained from the procedure described above, to their observed values shown in the right panels of Figs 1 and 2. Results are listed in Table 1 under "1974", the formal errors being: \( \sigma_A \sim \pm 0.6 - 1.5 \text{mmag} \) for \( k = 0 \) and 1 and \( \sigma_A \sim \pm 0.5 - 0.8 \text{mmag} \) for \( k = 2 \) and 3, and \( \sigma_\phi \sim \pm 0.02 - 0.04 \). Shown in the right panels of Figs 1 and 2 are lines calculated with those parameters; they
fit the points quite well (the only significant exception being $\phi_{2,\text{min}}$ in Fig.1). This implies that the parameters of the Fourier components did not change significantly during two nights.

We now compare the amplitudes of the Fourier components with those obtained from the seasonal mean light curves (Section 2).

1) The amplitude of the superhump fundamental mode $A_{0}^{SH} = 7.1\text{ mmag}$ was surprisingly large. This shows that this mode, commonly considered negligible, may occasionally contribute significantly to the observed light curve.

2) The amplitudes of the orbital overtones $A_{1}^{orb} = 8.2$ and $A_{2}^{orb} = 4.8\text{ mmag}$ were larger, than that of the fundamental mode. This means that the shape of the orbital light curve may occasionally differ considerably from a simple cosine-wave. A good illustration is provided by the mean orbital light curve observed by Solheim et al. (1998, Fig.10) during their two-week WET campaign in 1990.

3) The amplitude of the negative superhump first overtone $A_{1}^{nSH} = 4.4\text{ mmag}$ was comparable to that of the fundamental mode ($A_{0}^{SH} = 5.8\text{ mmag}$) which suggests that the shape of the negative superhump light curve may occasionally differ considerably from a simple cosine-wave. Worth adding is that the amplitude of negative superhumps is highly variable (see Provencal et al. 1995, Fig.6).

4. Conclusions

It has been rather obvious that large variations in the shape of the observed light curve of AM CVn are due to the interference between its three components: the superhumps, the negative superhumps and the orbital variations. Results presented above show that the shapes of the light curves of those three components are also variable and this contributes significantly to the observed variations.

The time scale of those variations could be determined only from detailed analysis of long series of observations covering several consecutive nights; our results suggest only that it is longer that 1 day.

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