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# Long-term photometric behavior of the eclipsing Z Cam-type dwarf nova AY Psc

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**Abstract** New eclipse timings of the Z Cam-type dwarf nova AY Psc were measured and the orbital ephemeris was revised. In addition, based on long-term AAVSO data, the outburst behaviors were also explored. Our analysis suggests that normal outbursts are quasi-periodic, with an amplitude of $\sim 2.5(\pm0.1)$ mag and a period of $\sim 18.3(\pm0.7)$ d. The amplitude vs. recurrence-time relation of AY Psc is discussed, and we conclude that this relation may represent general properties of dwarf nova outbursts. The observed standstill ends with an outburst, which is inconsistent with the general picture of Z Cam-type stars. This unusual behavior was considered to be related to mass-transfer outbursts. Moreover, the average luminosity is brighter during standstills than during outburst cycles. The changes in brightness mark variations in $\dot{M}_2$ due to the fact that the disk of AY Psc is nearly steady state. $\dot{M}_2$ value was limited to the range from $6.35\times10^{-9}$ to $1.18\times10^{-8}\,M_\odot\,\mathrm{yr}^{-1}$. More detailed examination shows that there are a few small outbursts present during standstills. These events with amplitudes of $\sim 0.5-0.9$ mag are very similar to the stunted outbursts reported in some nova-like cataclysmic variables. We discussed several possible mechanisms and suggested that the most reasonable mechanism for these stunted outbursts is a changing mass-transfer rate.

**Key words:** binaries: close — stars: cataclysmic variables — stars: individual (AY Psc)

## 1 INTRODUCTION

Z Cam stars are a subtype of dwarf nova-type (DN) cataclysmic variables (CVs) exhibiting protracted standstills about 0.7 mag below maximum brightness, during which the brightness stays constant (Warner 1995). The duration of standstills has a large range from tens of days to years. These stars exhibit U Gem-type outbursts but the standstills are similar to the behavior of nova-like CVs (NLs). Osaki (1974) proposed an interpretation of standstills for the first time in which the accretion disk was in the steady stage. After that, these systems are defined as an intermediate between stable NLs and unstable DNe (Smak 1983). Moreover, a model for the standstills was presented by Meyer & Meyer-Hofmeister (1983). This model suggested that the mass transfer rate in Z Cam stars is close to a critical rate (i.e. $\dot{M}_2 \approx \dot{M}_{\mathrm{crit}}$). A system with $\dot{M}_2 < \dot{M}_{\mathrm{crit}}$ will generate U Gem-type normal outbursts. When $\dot{M}_2 > \dot{M}_{\mathrm{crit}}$, the system enters standstill behaving like NLs. Moderate fluctuation in $\dot{M}_2$ could produce Z Cam-type light curves (Lin et al. 1985; Buat-Ménard et al. 2001). Changes in $\dot{M}_2$ have generally been explained as irradiation effects of the secondary star's surface by the accretion disk (Meyer & Meyer-Hofmeister 1983). As expected, the average brightness in NLs was higher (by $\sim 3$ mag) than in DNe at the same orbital period (Warner 1995). On long timescales, the average brightness in Z Cam stars is expected to follow changes in $\dot{M}_2$ because their disks are nearly steady state.

AY Psc was classified as a Z Cam star due to its occasional standstills and normal DN outbursts (Mercado & Honeycutt 2002). It was identified as a CV candidate by Green et al. (1982) and first studied in detail by

Szkody et al. (1989) who presented $B-$ and $V-$band light curves showing deep eclipses with an orbital period of 5.13 h. Later, an orbital ephemeris was provided by Diaz & Steiner (1990) who also revised the orbital period to be 5.2 h. The system parameters were derived by Howell & Blanton (1993) through photometric analysis and by Szkody & Howell (1993) using time-resolved spectroscopy. According to Szkody & Howell (1993), AY Psc contains a massive $\sim 1.31\,M_\odot$ white dwarf and a $\sim 0.59\,M_\odot$ companion, for a total system mass of $\sim 1.9\,M_\odot$, which is well in excess of the Chandrasekhar limit ($\sim 1.4\,M_\odot$) and therefore is a ballpark estimate for potential SN Ia progenitors. However, we still know little about its outbursts because of the paucity of long-term photometric data. Fortunately, many $V$-band data from the American Association of Variable Star Observers (AAVSO) covering a timescale of $\sim 6$ yr provide a good opportunity to ascertain the outburst properties. Moreover, the deeply eclipsing nature of AY Psc can be used to probe orbital period changes. From an evolutionary perspective, the period analysis can offer some clues concerning the orbital evolution and circumbinary companions. The most common method for determining period variations is to analyze the observed-calculated ($O-C$) diagram. We have applied this method several times in the past few years to study a few eclipsing CVs such as Z Cha (Dai et al. 2009), OY Car (Han et al. 2015), V2051 Oph (Qian et al. 2015) and GSC 4560-02157 (Han et al. 2016). In this paper, we present new CCD photometric observations of AY Psc and update the orbital ephemeris. Then its outburst properties are analyzed by using the AAVSO data.

## 2  OBSERVATIONS AND DATA PREPARATION

New CCD photometric observations of AY Psc were carried out by using several different telescopes. They were: the 60 cm and the 1.0 m reflecting telescopes utilizing Andor DW436 2K CCD cameras at Yunnan Observatories (YNO); the 85 cm and the 2.16 m telescopes at Xinglong Station administered by National Astronomical Observatories, Chinese Academy of Sciences (NAOC); and the 2.4 m Thai National Telescope (TNT) administered by National Astronomical Research Institute of Thailand (NARIT). The 85 cm telescope had an Andor DW436 1K CCD camera and the 2.16 m telescope was equipped with a PI $1274 \times 1152$ TE CCD. The TNT is a Ritchey-Chrétien with two focuses and an ULTRASPEC fast camera was attached to it. During observations, no filters were used in order to improve the time resolution. The aperture photometry package of IRAF was used to reduce the ob-

served CCD images. Differential photometry was performed, with a nearby non-variable comparison star.

Figure 1 displays four eclipsing profiles observed with different telescopes. As done by Diaz & Steiner (1990), new mid-eclipse times are determined by using a cubic polynomial fitting. The errors are standard deviation values. All mid-eclipse times and errors are listed in Table 1.

To investigate the outburst properties, long-term light curves are required. Figure 2 shows the entire AAVSO light curve of AY Psc in $V$- and $R$-band from 2010 August 19 – 2016 November 29. Here we only used digital photometric data because errors in the visual data are too large ($\sim 0.3 - 0.5$ mag). The digital photometric observations began in 2010 August and over 1400 observations from 26 observers are included in Figure 2. The errors are estimated to within 0.1 mag for the bright state (during outburst and standstill) and within 0.2 mag for quiescence using the comparison and check stars with known magnitudes in this field by these observers. Due to the fact that AY Psc is an eclipsing system, such data have been prepared by omitting the data during eclipse before the analysis. Although fragmentary data and gaps are present, the standstill is clearly visible in the light curve. The long-term light curve was partitioned into seven data sets by the gaps. The best data occur after JD 2457553, where the density of observations is $1.7\,\mathrm{d}^{-1}$ and every day contains at least one data point. Continuous outbursts in this data set are plotted in Figure 4 and reveal a feature similar to a sine wave. More detailed analysis is given in Section 3.2.

## 3  RESULTS AND DISCUSSION

### 3.1  Revised Ephemeris

Mid-eclipse times of AY Psc have been published in the literatures by two authors (e.g. Diaz & Steiner 1990 and Gülsecen et al. 2009). Diaz & Steiner (1990) reported nine mid-eclipse times and showed no sign of any orbital period change. Combining the previous data with our observations, the latest version of the $O-C$ diagram is displayed in Figure 3. The $O-C$ values of all available data are computed with the linear ephemeris given by Diaz & Steiner (1990)

$$\mathrm{Min.I} = \mathrm{HJD}\,2447623.3463 + 0.2173209 \times E, \quad (1)$$

where HJD 2447623.3463 is the initial epoch and 0.2173209 d is the orbital period. The best-fitting linear ephemeris to all the eclipse times of AY Psc is

$$\mathrm{Min.I} = \mathrm{HJD}\,2447623.34628(2) + 0.21732061(1) \times E. \quad (2)$$
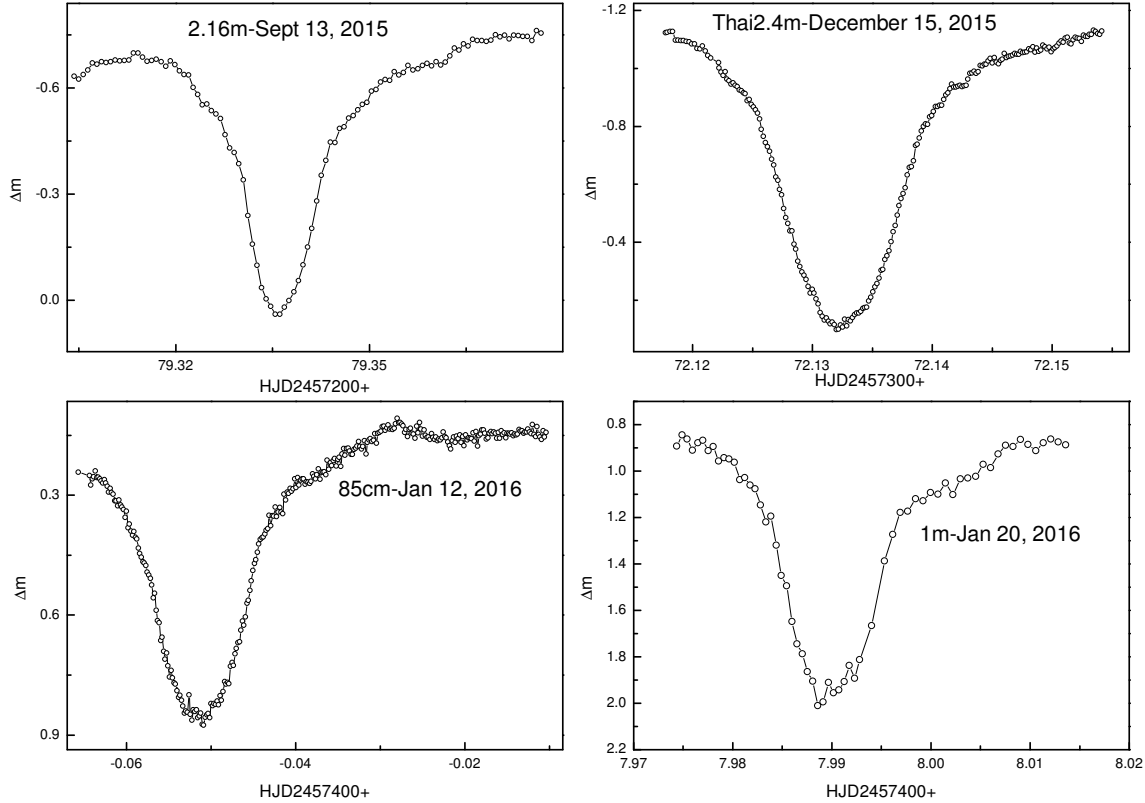
**Fig. 1** Four eclipse profiles of AY Psc obtained with four different telescopes in China and in Thailand.

**Table 1** New CCD Mid-eclipse Times of AY Psc

| Date | Min.(HJD) | $E$ | $O - C$ | Error | Filter | Telescope |
|------|-----------|-----|---------|-------|--------|-----------|
| 2012 Dec 13 | 2456275.09576 | 39811 | –0.01289 | 0.00011 | N | 60 cm |
| 2015 Sep 13 | 2457279.33629 | 44432 | –0.01224 | 0.00005 | N | 2.16 m |
| 2015 Sep 24 | 2457290.20122 | 44482 | –0.01335 | 0.00019 | N | 1 m |
| 2015 Dec 15 | 2457372.13246 | 44859 | –0.01209 | 0.00003 | N | Thai-2.4 m |
| 2016 Jan 12 | 2457399.94876 | 44987 | –0.01287 | 0.00003 | N | 85 cm |
| 2016 Jan 20 | 2457407.98993 | 45024 | –0.01257 | 0.00008 | N | 1 m |

The dashed line in Figure 3 represents the revised linear ephemeris. However, the residuals from this ephemeris show some deviations and the orbital period does not seem to be constant. This may be caused by some of the unknowns or a true period change. However, there is still no more evidence to support this change. Therefore, further observations are critically required to ascertain the changes in orbital period of this system.

### 3.2 Outburst Properties

#### 3.2.1 Normal outbursts and the K-P relation

In Figure 2 we show the long-term AAVSO light curve of AY Psc during 2010 August−2016 November. The data are divided into seven segments because a lot of data are missing. A detailed view of the light curves reveals three main features: normal outburst, standstill and stunted outburst. During normal outburst, the duty cycle of AY Psc approaches $100\%$. This behavior is thought to be due to $\dot{M}_2 \approx \dot{M}_{\mathrm{crit}}$ (Lin et al. 1985; Warner 1995). The system rises from $V \approx 17.1$ at minimum to $V \approx 14.6$ at maximum in $6 - 8\,\mathrm{d}$, exhibiting a mean outburst amplitude of $\sim 2.5(\pm 0.1)\,\mathrm{mag}$.

Figure 4 displays a best outburst data set for AY Psc covering $169\,\mathrm{d}$ (2016 Jun 14−2016 Nov 29). A sine curve fit was applied to the eight outburst cycles in Figure 4, giving a recurrence time of $\sim 19.03(\pm 0.04)\,\mathrm{d}$. However, the full light curve contains at least four out-
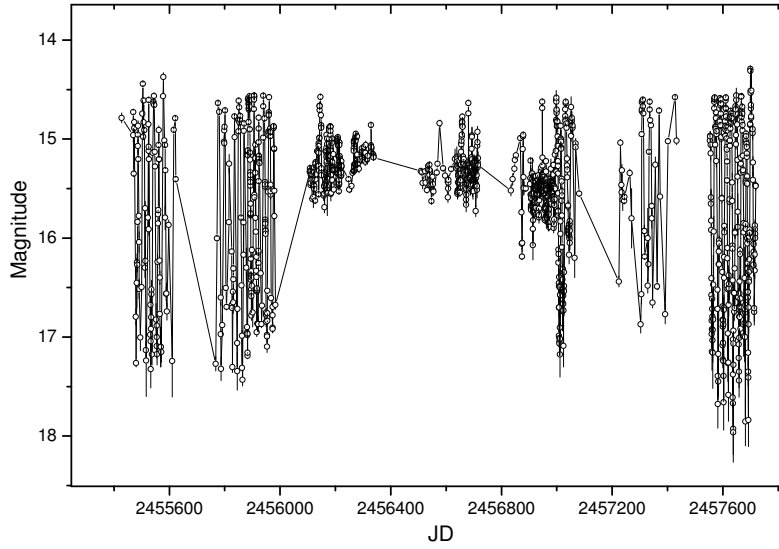
**Fig. 2** The long-term light curve of AY Psc from AAVSO observations during 2010 August−2016 November. Note the presence of obvious standstills at $15.3(\pm0.2)$ mag.
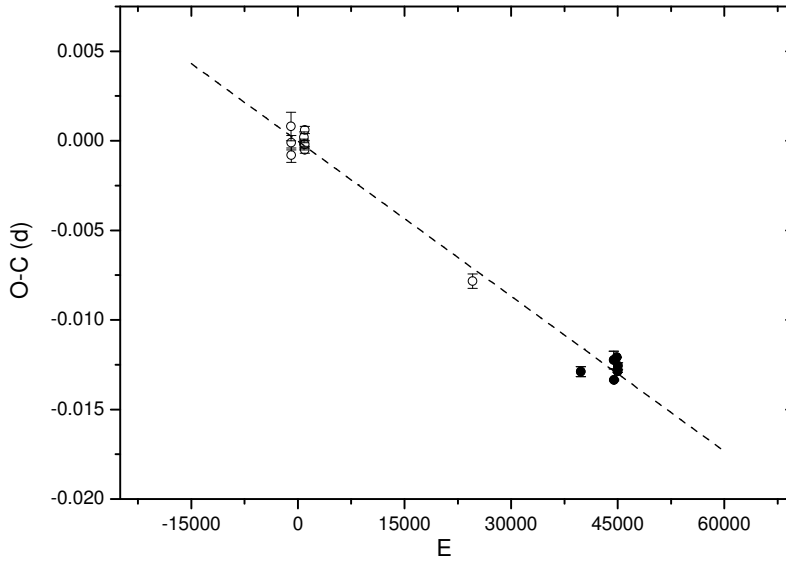


**Fig. 3** $O - C$ diagram of AY Psc. The open circles and solid circles denote the data in the literature and our observations, respectively. The dashed line represents the best-fitting linear ephemeris.

burst segments. To verify this result, analysis of all these outburst segments is required.

Figure 5 shows all outburst data sets and their associated power spectrums. The power spectrums correspond to the periods between 17.7 and 18.5 d, which is smaller than the period from the sine fitting ($\sim 19.03$ d). This implies that the outburst in AY Psc is not strictly periodic but rather quasi-periodic.

Kukarkin & Parenago (1934) first noted that there was a relation between the outburst amplitude ($A_n$) and the outburst recurrence time ($T_n$) for DNe and recurrent novae. After that, this relation has been revised and improved many times to constrain its application range. Finally, a general correlation was found by analyzing normal outbursts in DNe (van Paradijs 1985). The most
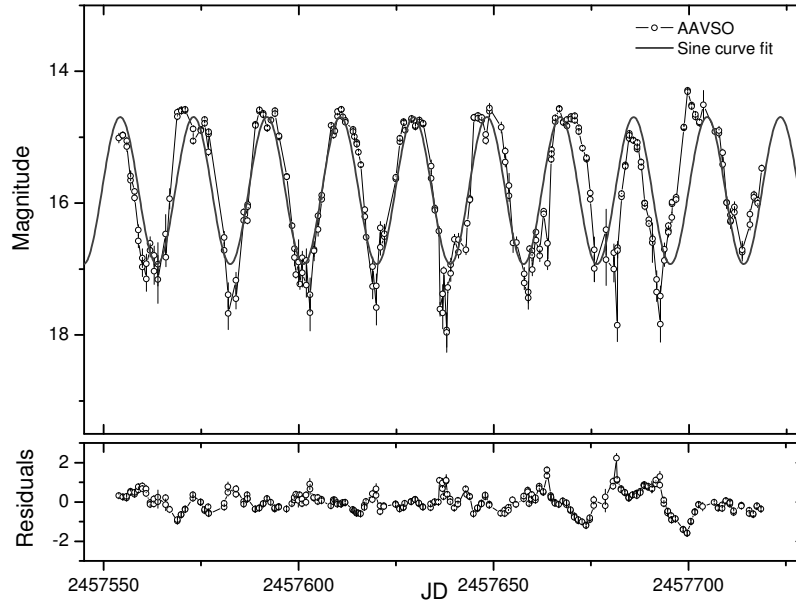
**Fig. 4** Continuous outbursts in AY Psc spanning $\sim 170$ d (2016 Jun 14−2016 Sept 27). The sine curve fit was superposed on this outburst segment, which gives a period of $\sim 19.03(\pm 0.04)$ d. The lower panel displays the fitting residuals from the sine wave.

recent version of the Kukarkin-Parenago (K-P) relation from Warner (1995) is as follows

$$A_n = 0.7(\pm 0.43) + 1.9(\pm 0.22)\log T_n. \qquad (3)$$

This is an empirical relation. Moreover, to explore if this relation is model-dependent, a theoretical K-P relation was derived by Kotko & Lasota (2012) using the disk instability model

$$A_n = C_1 + 2.5\log T_n, \qquad (4)$$

where the constant term

$$C_1 = 2.5\log 2\tilde{g} - 2.5\log t_{\text{dec}} + BC_{\max} - BC_{\min},$$

depends on the properties of the white dwarf and the viscosity parameter $\alpha$. The outburst parameters of AY Psc and the K-P relation are plotted in Figure 6. The open squares represent statistical data from the AAVSO database, the red solid line refers to the empirical K-P relation and red dashed lines denote its upper and lower uncertainties. However, the observational data were not covered in this relation. Note that this relation is only significant for systems with $A_n > 2.5$ mag (Warner 1995). The lower uncertainty of the empirical relation follows the overall trend of observational data reasonably well because the amplitude of AY Psc falls on the boundary of $2.5$ mag. Therefore, the K-P relation for AY Psc will be roughly replaced by the lower limit of the empirical relation

$$A_n = 0.27 + 1.68\log T_n. \qquad (5)$$

Based on those descriptions, we suggest that the K-P relation may represent a common characteristic of DN outbursts.

### 3.2.2 Standstills and brightness modulation

Figure 7 shows the standstill signal at $15.3(\pm 0.2)$ mag extracted from Figure 2 during the period from 2012 June 29 to 2015 January 1. The upper panel of Figure 8 displays a well-observed transition from standstill to outburst, where we see an unusual characteristic behavior that differs from what is exhibited by most Z Cam stars. This standstill ends with an outburst (see Fig. 8). However, the currently used model of Z Cam stars predicts that a standstill can only be terminated by a decline to quiescence rather than an outburst (Buat-Ménard et al. 2001). Before several of the the unusual Z Cam systems were discovered, only one recorded standstill in the prototype star Z Cam was observed to terminate in a rise to maximum (Warner 1995; Oppenheimer et al. 1998). Recently, this rare behavior was observed in several anomalous Z Cam-type stars such as AH Her, IW And, V513 Cas and ST Cha (Simonsen 2011; Simonsen et al. 2014). A plausible explanation for this behavior was proposed by Hameury & Lasota (2014), who indicated that mass-transfer outbursts can reproduce the observed properties of these unusual systems. This implies that the changes in mass transfer from the secondary star are responsible for changes in brightness on longer timescales.
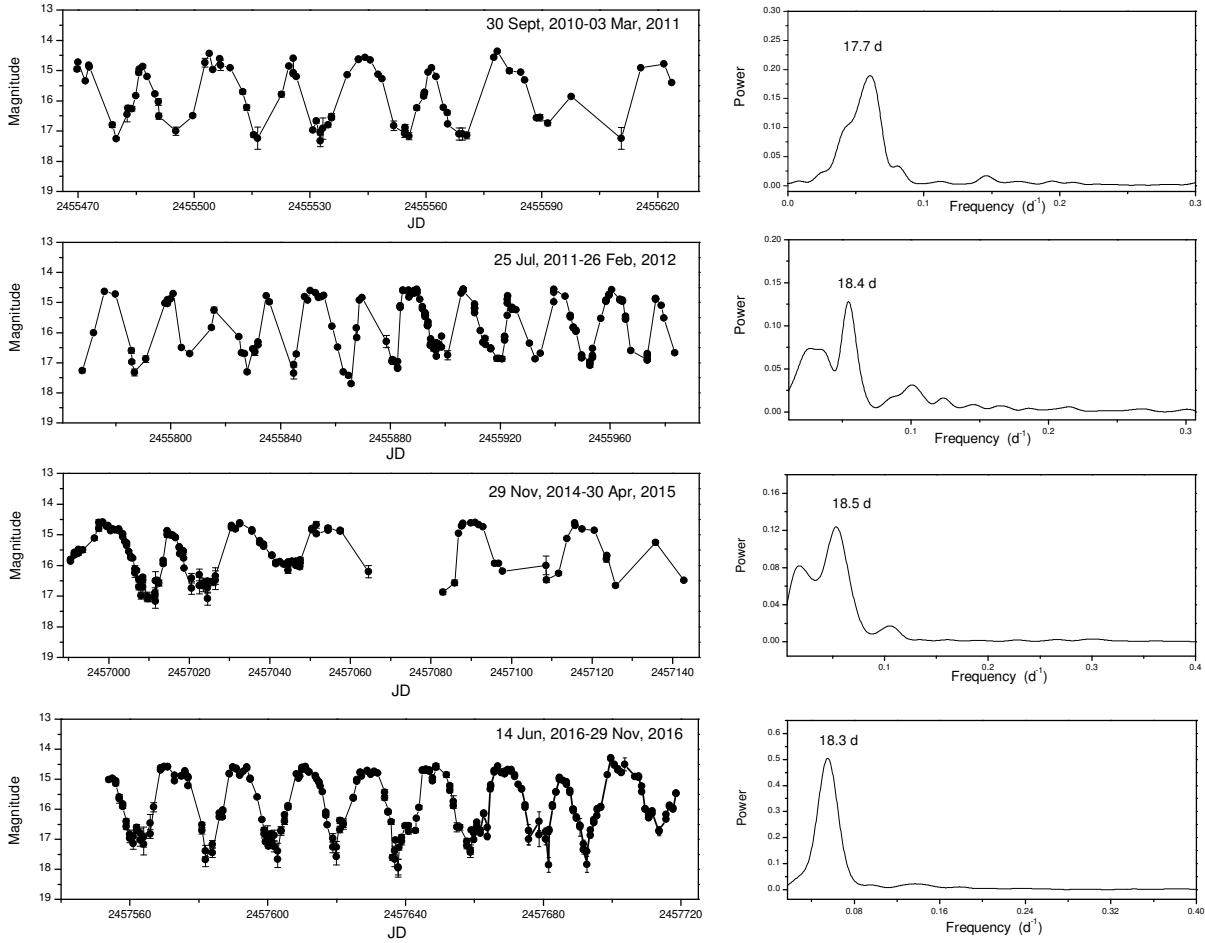
**Fig. 5** Four outburst segments and corresponding power spectrums. The power spectrums indicate that the outbursts are quasi-periodic, with periods between 17.7 and 18.5 d.

For Z Cam-type systems, a direct test is to compare the standstill and outburst brightness. In effect, there have been several studies that investigated this aspect (Lortet 1968; Oppenheimer et al. 1998; Honeycutt et al. 1998). To clearly reveal the mass-transfer variations, the mean brightness during standstills and the outbursts were calculated by averaging long-term AAVSO data. In computing the mean magnitude values, only full cycles were averaged. For outbursts, two mean values were measured per outburst cycle, overlapping by one-half cycle. For standstills, means were computed for successive intervals of several tens of days. The mean brightness values of all data are plotted in Figure 9. The red dots in Figure 9 represent the means during standstills and the black dots denote the means during outbursts. Clearly, the average magnitudes during standstills are brighter than during outburst intervals. This result is consistent with previous authors (e.g. Oppenheimer et al. 1998; Honeycutt et al. 1998). Moreover, the trend in Figure 9 also implies there

are changes in $\dot{M}_2$, in agreement with the general picture of standstills. The green solid line marks the transition between outburst cycles and standstills, corresponding to $\dot{M}_{\rm crit}$. Frank et al. (2002) give an expression for $\dot{M}_{\rm crit}$

$$\dot{M}_{\rm crit} \simeq 3 \times 10^{-9} (P_{\rm orb}/3)^2 M_\odot \, {\rm yr}^{-1} , \qquad (6)$$

where $P_{\rm orb}$ is in hours. For AY Psc, with $P_{\rm orb} = 5.22\,{\rm h}$, we find $\dot{M}_{\rm crit} \simeq 9.07 \times 10^{-9} \, M_\odot \, {\rm yr}^{-1}$. Buat-Ménard et al. (2001) pointed out that $\dot{M}_2$ will vary by about 30% around $\dot{M}_{\rm crit}$. More specifically, $\dot{M}_2$ in AY Psc should be restricted to the range from $6.35 \times 10^{-9}$ to $1.18 \times 10^{-8} \, M_\odot \, {\rm yr}^{-1}$.

### 3.2.3 Stunted outbursts in AY Psc

More detailed inspection of the AAVSO data reveals that there are diverse behaviors during standstill. Note that the brightness of the standstill is not constant, but rather keeps fluctuating. Oscillations with an amplitude
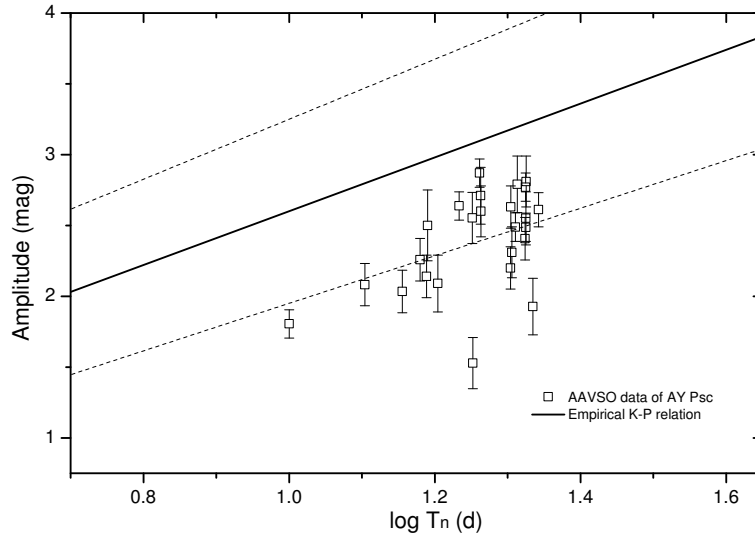
**Fig. 6** Comparison of the K-P relation and AAVSO data for AY Psc. The open squares represent statistical data, the red solid line refers to the empirical K-P relation (Warner 1995) and red dashed lines denote its upper and lower uncertainties.
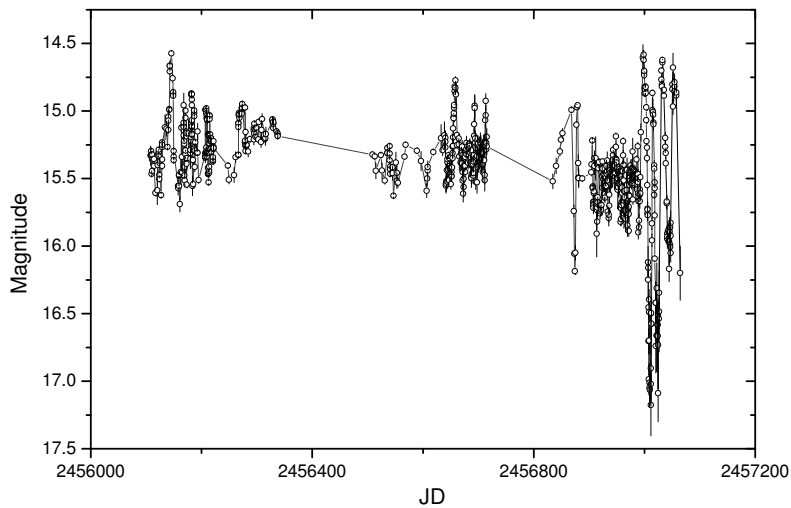


**Fig. 7** The standstill data at $15.3(\pm0.2)$ mag extracted from Fig. 2 during the period from 2012 June 29 to 2015 January 1. It is clear that there are small amplitude oscillations present during standstills.

of $\sim 0.2$ mag can be seen by eye in Figures 7 and 8. Moreover, we find occasional outburst-like events during standstill, as shown in Figure 10. These events are best characterized as small amplitude outbursts, which have properties very similar to the stunted outbursts seen in some NLs (e.g. Honeycutt et al. 1995, 1998; Honeycutt 2001; Honeycutt et al. 2014; Warner 1995; Hoard et al. 2000; Ramsay et al. 2016).

Table 2 summarizes the properties of stunted outbursts in AY Psc. The stunted outbursts in Figure 10 are visible with amplitudes of $\sim 0.5-0.9$ mag and full width

at half maximums (FWHMs) of $\sim 2 - 14$ d. The rises are slower than the declines, implying that the outbursts are Type B (inside-out). However, to date, the origin of stunted outbursts is still uncertain. Some possible mechanisms are proposed to account for the stunted outbursts, including a disk truncated by the magnetic field of the white dwarf or a very hot white dwarf, DN outbursts being related to the standard disk instability and mass transfer modulations (Honeycutt et al. 1998; Honeycutt 2001; Honeycutt et al. 2014; Ramsay et al. 2016). For AY Psc, a truncated disk mechanism can be ruled out because the
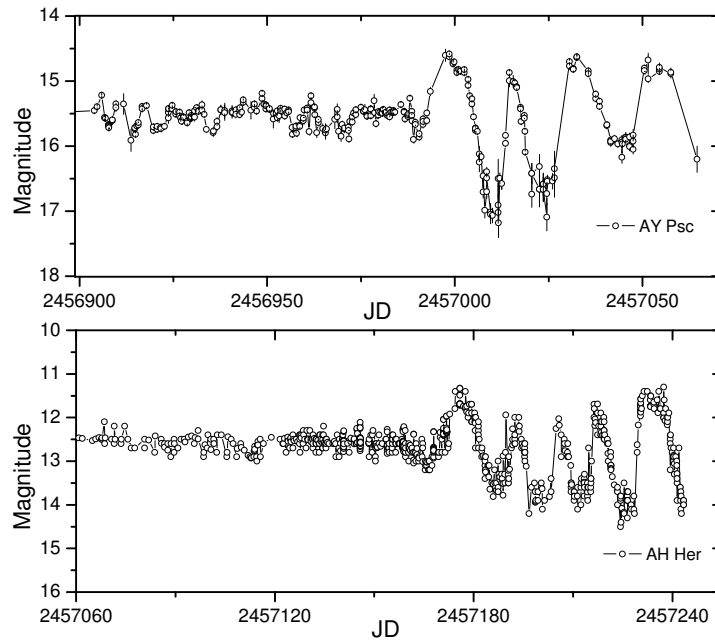
**Fig. 8** *Upper panel*: a transition from standstill to outburst interval in AY Psc. *Lower panel*: a transition from standstill to outburst interval in AH Her. The two transitions terminate in an outburst, in disagreement with current theoretical prediction and observations.
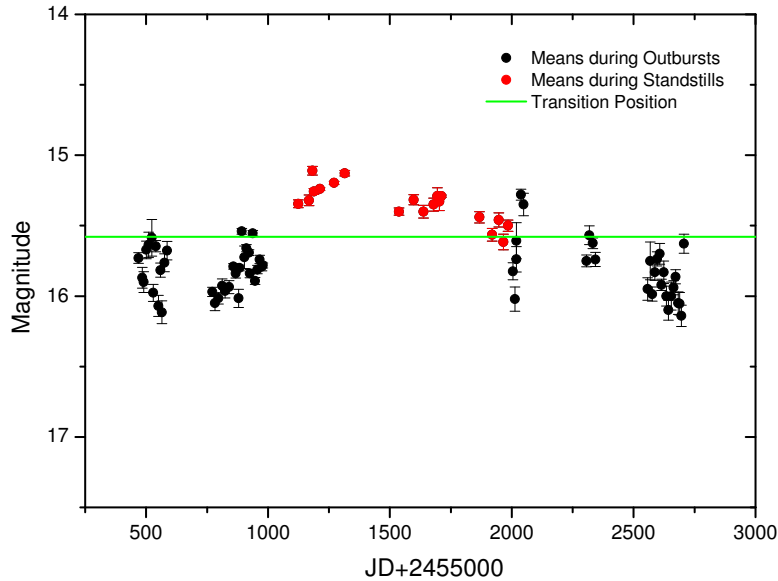


**Fig. 9** Comparison of the outburst and standstill mean brightness in AY Psc using all AAVSO data. The red dots are the means during standstills and the black dots denote the means during outburst cycles. The green line represents the transition position.

inside-out outbursts (Type B) in a truncated disk are infrequent (Honeycutt et al. 1998). During standstill, $\dot{M}_2$ from the secondary star exceeds $\dot{M}_{\mathrm{crit}}$, and the disk stays in steady state, without DN outbursts. In addition, Warner (1995) indicated that DN outbursts have faster rise times than decline times by a factor of $\sim 2$ (i.e. Type A out-

bursts), which is not compatible with the stunted behaviors of AY Psc. Therefore, the disk instability may not be the cause of stunted outbursts. It seems that a changing mass transfer is a reasonable candidate mechanism for these stunted behaviors. First, a steady-state disk allows the brightness to follow changes in mass transfer.

**Table 2** Basic Parameters of the Stunted Outbursts in AY Psc

| Outburst | JD | Ampl. (mag) | FWHM (d) | $\tau_{rise}$ (d) | $\tau_{fall}$ (d) |
|---|---|---|---|---|---|
| 1 | 2456145 | 0.89 | 7.3 | 21 | 10 |
| 2 | 2456273 | 0.53 | 14.1 | 15 | 11 |
| 3 | 2456658 | 0.68 | 6.5 | 8 | 10 |
| 4 | 2456693 | 0.56 | 2.8 | 3 | 2 |
| 5 | 2456713 | 0.59 | 2.1 | 2 | 1 |
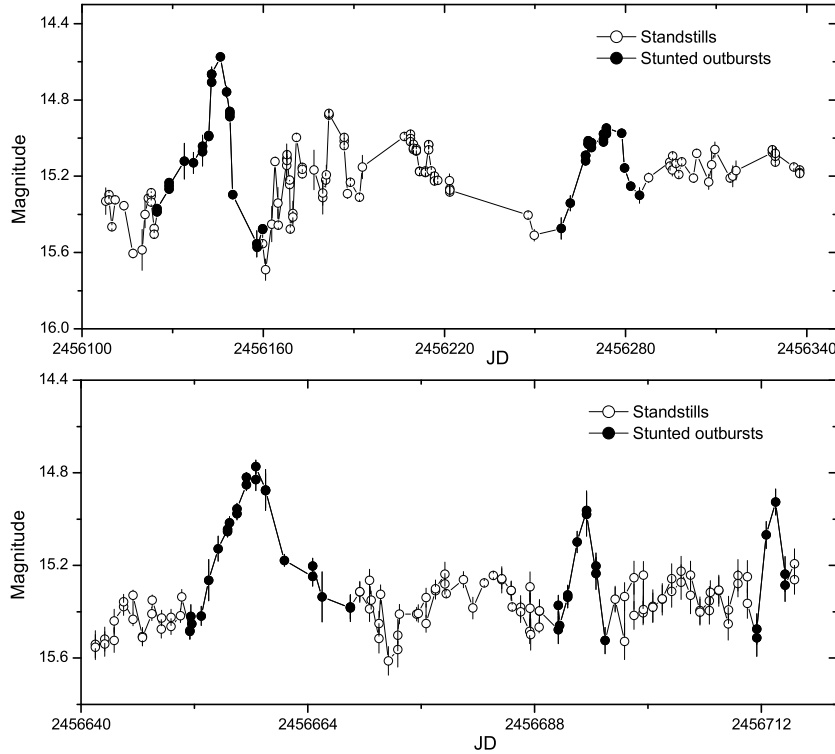


**Fig. 10** Five stunted outbursts during standstills showing amplitudes of $\sim 0.5-0.9$ mag. The characteristics of the stunted outbursts are summarized in Table 2.

Second, Hameury & Lasota (2014) studied the disk's response to a mass transfer outburst during standstills and reproduced an outburst with an amplitude of $\sim 0.8$ mag starting from a steady state disk. Meanwhile, the possible origins of the mass transfer outbursts were also discussed by these authors. Nevertheless, these stunted outbursts are not well understood so far.

## 4 SUMMARY

We have presented the photometric results of the eclipsing Z Cam-type star AY Psc using our observations together with AAVSO data. Our analysis focuses on the orbital period and outburst properties. The main conclusions of this paper can be summarized as follows.

 (i) The orbital period has been revised from 0.2173209 d to 0.21732061 d.

 (ii) The duty cycle of AY Psc is close to 100%.
(iii) The observed standstill, extending from 2012 June 29 to 2014 December 1, ended with an outburst rather than a decline to quiescence, which is rarely seen in similar systems.
(iv) During the standstill, several stunted outbursts were present.

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