Conservative mass transfer on eclipsing binary AE Phe from O-C diagram analysis

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Abstract. Eclipsing binary is an edge-on binary system where the components appear to be eclipsing one another. Eclipsing binaries therefore give a lot of information on the systems’ behavior, one of them from their period change. O-C diagram exhibits the deviation of the observed time of minimum from the calculated ones and its analysis will reveal the responsible mechanism, such as a hidden third component, apsidal motion, and mass transfer. AE Phe (V = 8.15 mag and spectral class G0V) is a W UMa W-type binary. Previous studies of its degree of contact have revealed AE Phe to be a shallow-contact binary. Photometric data were taken using PROMPT (Panchromatic Robotic Optical Monitoring and Polarimetry Telescopes), CTIO on October 4th, 2013 on four filters: B, V, R, and I. The Kwee and van Woerden (1956) method was also used to determine AE Phe’s time of minimum. Analysis of the O-C diagram (taken from 1975 toward our observation) suggest that the period of AE Phe shows a long-term continuous increase. These period increase and degree of contact suggest that AE Phe is undergoing thermal relaxation oscillation (TRO) and is evolving to a broken-contact phase, with a possibility of angular momentum loss (AML) through magnetic braking.

1. Introduction

An eclipsing binary is a binary system whose orbital motion is in a plane sufficiently edge-on to the observer. Consequently, the two stars will take turns eclipsing each other from our sight during each orbital period. In general, a photometric study of an eclipsing binary system has one or both of the following goals [1]: 1) to determine the time of minimum light and further to deduce precise orbital period, and 2) to analyze the entire light curve and provide a direct way to determine the fundamental stellar parameters of the system. The determination of the time of minimum (hereafter referred as ToM) light from photometric observations will reveal whether or not the period is changing. Variations in the orbital period give us indirect information of the mechanism responsible for the changes, such as mass transfer, a hidden third component, and apsidal motion.

In this paper, we aim to calculate the conservative mass transfer of the southern hemisphere eclipsing binary AE Phe (V = 8.15 mag and spectral class G0V). The AE Phe system has been identified as a W-UMa type binary with a short period of 0.362 days. The most recent analysis of the AE Phe system was reported by He et. al (2009) [2]. They presented the photometric solutions and the O-C diagram analysis of AE Phe. From the photometric solutions, they found
Table 1. Coordinates of the program (AE Phe), comparison, and check star.

| Star            | RA (J2000.0) (hh:mm:ss) | Dec (J2000.0) (dd:mm:ss) |
|-----------------|-------------------------|--------------------------|
| AE Phe          | 01:32:32.3              | -49:31:41.3              |
| Comparison star | 01:32:44.3              | -49:31:14.7              |
| Check star      | 01:32:22.6              | -49:31:27.0              |

that AE Phe has a degree of contact of $f = 14.6(\pm)0.5\%$, meaning that the system is a W-subtype shallow-contact binary. They also gave a linear ephemeris in Heliocentric Julian Date (HJD)

$$\text{Min I} = \text{HJD}2447852.6995 + 0^d.36237307 \times E.$$  \hspace{1cm} (1)

From the $O-C$ diagram analysis, they found the period of AE Phe shows a long-term continuous increase at a rate of $dP/dt = +6.17(\pm0.44) \times 10^{-8}$ days/year that can be explained by mass transfer from the less massive to the more massive component.

2. Observation and Data Analysis

The observation of AE Phe was done on October 4th, 2013 at the Cerro Tololo Inter-American Observatory in Chile with the 0.4 m PROMPT-5 telescope ($f/11.3$) on four filters, the $B$, $V$, $R$, and $I$ band. The coordinates for the program, comparison, and check star are listed in table 1.

The comparison star is 5.7 magnitudes fainter than the program star and was the only reasonable choice, considering our photometric system field of view is 10 arcmin × 10 arcmin. The CCD images reduction was performed directly by PROMPT and we received 40 clean images, 10 images for each band. To process the observed images, we carried out aperture and differential photometry using the Image Reduction and Analysis Facility (IRAF) PHOT task. The complete CCD photometric light curves in four bands are shown in figure 1 with HJD as the abscissa and relative instrumental magnitude as the ordinate.

Figure 1. Complete CCD photometric light curves of AE Phe on $BVRJ$ filters on October 4th, 2013 using PROMPT. The error bar for each data point is represented in grey line. The error bar for each data point is 0.0875 mag, 0.0585 mag, 0.088 mag, and 0.0815 mag for the $B$, $V$, $R$, and $I$ band, respectively.

Only the $B$ and $V$ band show a 'well' feature, the signature of an eclipse occurring. The $R$ and $I$ band only show the ascending branch of the 'well' feature. We think this is because of an observational error in the $R$ and $I$ band, therefore our research is primarily focused on the $B$ and $V$ band. The observed ToM was calculated using the Kwee and van Woerden method.
Table 2. Times of primary minimum light on $BVR$ of AE Phe

| No. | HJD   | Error (days) | Filter |
|-----|-------|--------------|--------|
| 1   | 2456569.5767 | 0.00019      | $B$    |
| 2   | 2456569.5807 | 0.00008      | $V$    |
| 3   | 2456569.5854 | 0.00045      | $R$    |

[3] written in Python and the times of minimum light for three bands are listed in table 2. The computation only converged and yielded solutions for the $B$, $V$, and $R$ band. The Kwee and van Woerden method requires a magnitude pair in the descending and ascending branch, with respect to a defined reflection axis, to calculate the time of minimum. Since the $I$ band only exhibits an ascending branch, a solution was not acquired. While the computation converged for the ToM calculation of the $R$ band, we do not think the mid-eclipse in the $R$ band is physical as it is located between two ascending branches. To determine the ToM from the three bands, we used a weighted mean and gave the weight ($w$) of 4, 5, and 1 to the $B$, $V$, and $R$ band, respectively. The time of primary minimum of AE on $BVR$ for our observation was found to be $\text{Min. I} = \text{HJD} 2456569.5769 \pm 0.05031$.

3. Results

3.1. $O-C$ Diagram

We observed only one time of primary minimum light for the AE Phe system. We then collected all reliable times of minimum available in the literature and current database to build the $O-C$ diagram. A total of 32 times of minimum light were used in our analysis, all primary minimums. The times of minimum have been collected from 1970 and obtained from Willamon (1975) [4]; Grønbech (1976) [5]; Walter and Duerbeck (1988) [6]; Maceroni and van’t Veer (1994) [7]; He et. al. (2009) [2]; and this paper. To analyze the $O-C$ diagram, we gave a weighting scheme based on the data acquisition instruments. We gave a weight of $w = 9.75$ for photoelectric photometric observations and a weight of $w = 10$ for CCD photometric observations. Using all the times of minimum light and the linear ephemeris in equation (1), we obtained a new ephemeris:

$$\text{Min. I} = \text{HJD} 2447852.6981 + 0.36237306 \times E.$$  \hspace{1cm} (2)

The $O-C$ values and the residuals for the quadratic ephemeris are shown in figure 2. It can be seen from figure 2 that the $O-C$ residuals form a parabola and using the least-square method, we obtained the following quadratic equation

$$[O - C] = 6.680 \times 10^{-11} E^2 + 7.230 \times 10^{-8} E + 1.769 \times 10^{-3}$$  \hspace{1cm} (3)

with $dP/dt = 1.3465(\pm 1.3441) \times 10^{-8}$ days/year or equivalent to 0.12 seconds per century. This means that the AE Phe system shows a long-term continuous period increase. The period increase rate that we attained is 4.5 times slower than what was reported in [2], which yielded a rate of $dP/dt = 6.17(\pm 0.44) \times 10^{-8}$ days/year. The $O-C$ diagram comparison between this paper and [2] is shown in figure 3.

3.2. Conservative Mass Transfer

The responsible mechanism of a parabolic $O-C$ diagram can be interpreted as the mass transfer from one of the components to the other. From the period change rate, we calculated the mass transfer rate of the AE Phe system using the equation from Hilditch (2001) [8]
Figure 2. O-C diagram of AE Phe based on the available times of primary minimum with the quadratic fit (red line) (a) and the residuals with respect to the quadratic fit (b).

\[
\frac{\dot{P}}{P} = \frac{3M_1(M_1 - M_2)}{M_1 M_2},
\]

with \(M_1, M_2\) are the masses of the primary and secondary component, \(P\) is the period of the system, \(\dot{P}\) is the period change rate, and \(M_1\) is the rate of the mass transfer of the primary component in solar mass per year. The mass of the primary and secondary component are \(M_1 = 1.38 M_\odot\) and \(M_2 = 0.63 M_\odot\) \[9\]. Using the period increase rate of \(dP/dt = 1.3465(\pm 1.3411) \times 10^{-8}\) days/year we obtained the conservative mass transfer rate of AE Phe of \(M_1 = 1.435 \times 10^{-8} M_\odot/\)year.
Figure 3. O-C diagram of AE Phe from Figure 2 with the quadratic fitting from this paper (red line) overlaid with the quadratic fitting from [2] (green line).

4. Discussions and Conclusions

From the O-C diagram and the period analysis, we found that the period of AE Phe is increasing continuously at a rate of \( \frac{dP}{dt} = 1.3465(\pm 1.3441) \times 10^{-8}\) days/year that corresponds to the conservative mass transfer rate of \( \dot{M}_1 = 1.435 \times 10^{-8} M_\odot/\text{year} \). This shows that the AE Phe system undergoes mass transfer from the less massive component to the more massive component (reverse mass transfer in contact). According to Lucy (1976) [10], Flannery (1976) [11] and Robertson and Eggleton (1977) [12], a binary system that evolves rapidly to contact will have its mass transfer direction reversed and if it does, the binary will widen, which should lead quickly to the breaking of contact. This is the thermal relaxation oscillation (TRO) theory: a contact binary will oscillate about an unstable equilibrium between its semi-detached phase and contact-phase. This also indicates that a contact binary with a period increase and a small degree of contact is evolving from its contact phase to a broken or marginal contact one. Considering AE Phe’s small degree of contact of \( f = 14.6(\pm 0.5\%) \) [2], this may suggest that AE Phe is currently evolving into a broken-contact phase and its evolution is controlled by TRO.

Hilditch [8] explained that theoretical models for mass-transfer show that mass-exchange/loss rate of \( 10^{-5} \) to \( 10^{-4} M_\odot/\text{year} \) can be expected to occur in a dynamical time-scale. Meanwhile, a mass transfer rate of \( 10^{-7} \) to \( 10^{-6} M_\odot/\text{year} \) in a thermal time-scale and a mass transfer rate of \( 10^{-11} \) to \( 10^{-8} M_\odot/\text{year} \) in a nuclear time-scale. From the obtained conservative mass transfer rate, we can expect AE Phe to undergo mass transfer on a nuclear time-scale. This is slower than what was predicted by the TRO model. Lucy (1976) [10] and Flannery (1976) [11], later confirmed by Robertson and Eggleton (1977) [12], predicted that contact binary that undergoes TRO will evolve on a thermal time-scale, faster than what we obtained in our analysis. Barnes et. al. (2004) [13] presented high-resolution doppler images of AE Phe, in which they found star spots in both components of the AE Phe system. This suggests that the AE Phe system is magnetically active, like other solar-like stars. Prior studies have also suggested the roles of magnetic braking in the formation and evolution of contact binaries ([14], [15], [16], [17], [18]).

We think the slower mass transfer rate of AE Phe is caused by angular momentum loss (AML) in the AE Phe system due to magnetic braking. The loss of angular momentum will decrease the separation between the two stars, therefore decelerating period increase and therefore decreasing the period increase and the conservative mass transfer rate. The role of magnetic braking to
prevent a W UMa type binary to reach a semi-detached configuration has been explained in detail by Rahunen (1981) [16]. The evolutionary scheme suggested that the loss of angular momentum can maintain a W UMa type binary in a shallow-contact phase and never reach breaking off contact. Qian (2001) [19], however, noted that this evolutionary scheme is still highly speculative.

Although we fit the O-C diagram with a parabolic term, we also note the scatter present in the diagram. Figure 2 (b) shows a scatter of more than 0.015 days. While we also think measurement and observational error have a big contribution to this scatter, we think the scatter in the residuals might show a slight sinusoidal term, especially from our observation. However, to definitively check whether or not a cyclical period change is present in the AE Phe system, the times of secondary minimum light need to also be analyzed, which we did not do in this research. Therefore, we can only suggest that there is a possibility of a cyclical period change in AE Phe and needs to be examined in future works.

Further CCD photometric observations of the AE Phe system on the BVRI band and both the primary and secondary minimum are needed to confirm and gain more information about the cause and nature of the period changes.

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