CCD Times of Minima for the W UMa Binary System OO Aquilae

Kevin B. Alton
70 Summit Avenue, Cedar Knolls, NJ 07927

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Abstract OO Aql was targeted for observation since its short orbital period (~0.5d) and eclipse duration (~3 hours) were amenable to investigation over a relatively short viewing campaign at a location with less than optimal viewing conditions. Analysis of clear filter CCD data collected over a ten-week period has led to a revised linear ephemeris equation (Min. I (hel.) = 2438613.1037 ± 0.0073 + 0.5067936 ± 0.0000003 E) for OO Aql.

1. Introduction

W Ursae Majoris variables belong to a class of eclipsing binaries whose component stars (spectral type A–F to early K) are synchronized with respect to orbital and rotational motion. A general review of W UMa systems was published by Maceroni *et al.* (1985). As rapidly rotating main sequence stars, they are close enough that gravitational interaction has pulled them into a teardrop shape. OO Aquilae is considered an "overcontact binary" since both stars share a common envelope of material (Wilson 2001). There has been a longstanding study of W UMa eclipsing binaries motivated by the hypothesis that these variables represent a pathway to better understanding the evolution of binary systems.

The variability of OO Aql was first discovered by Hoffleit (1932) but Binnendijk (1968) published the first complete light curves from this binary system. Photoelectric light curves for OO Aql have been reported by a number of other authors, including Lafta and Grainger (1985), Demircan and Güdür (1981), Essam *et al.* (1992), Gurol (1994), and more recently, Djurašević and Erkapić (1998). Rucinski (1995) observed OO Aql as part of a radio survey of W UMa systems, while ultraviolet light curves were reported by Hrivnak *et al.* (2001). OO Aql consists of two G5-type stars which are about the same mass as but slightly more evolved than our Sun. This system varies in visual magnitude from 9.2 to 10.1 just under twice a day (period ~0.50679d). Specifically, OO Aql belongs to the subclass of A-type W UMa binaries since the more massive ($M1 = 1.04\ M_{\odot}$) rather than less massive constituent ($M2 = 0.88\ M_{\odot}$) is eclipsed at primary minimum (Hrivnak 1989). As is typical with A-type W UMa systems, the temperature of the primary star is only slightly higher than the secondary. Hrivnak (1989), among many other observers, reported an orbital inclination angle of ~90°; our view of this system is nearly edge-on. OO Aql is in many ways ideally suited for study by astronomy students and interested amateurs. This relatively bright variable is easily within the detection limits of a consumer-grade CCD camera coupled with a modestly-sized telescope.

During the summer and early fall months this system is well positioned for mid-latitude observers in the Northern Hemisphere.

2. Observations and data reduction

2.1. Astrometry

Images of OO Aql were matched against the standard star fields provided in MPO CANOPUS (V7.6.4.6, Minor Planet Observer 2003). The *MPO Star Catalog* bundled with the CANOPUS software is a mixture of the *Tycho 2* (Høg *et al.* 2000) and *USNOA2.0* (Monet *et al.* 1998) catalogues assembled using all Tycho 2 stars brighter than magnitude 11 and USNO A2.0 stars brighter than magnitude 15.3 also possessing a *B–R* magnitude in the range of 0.50 to 1.50.

2.2. Photometry

Clear filter CCD photometric readings began on July 3, 2005. Equipment included a 0.2-meter Celestron Nexstar 8 GPS (f/6.3) with an SBIG ST-402ME CCD camera mounted at the Cassegrain focus. All imaging was performed over a 10-second unbinned exposure period with thermoelectric cooling regulated to maintain the chip 20°C below the initial ambient temperature. Barring clouds, a typical session, which was centered around the tabulated minima listings provided at the AAVSO website for eclipsing binaries, lasted from two to three hours, with images taken every forty-five seconds. Clock time was updated via the Internet Time Server immediately prior to each session. Image acquisition (raw lights, darks, and flats) was performed using SBIG CCDSOFT 5 while calibration and registration were accomplished with AIP4WIN (V2.1.0, Berry and Burnell 2005). MPO CANOPUS provided the means for further photometric reduction (differential instrument magnitudes) using at least four nonvarying comparison stars to ultimately calculate ephemerides and orbital period. No color or air mass corrections were applied.

3. Results and discussion

3.1. Astrometry

OO Aql (Figure 1) is located in a stellar-rich region of the sky so that finding comparison stars within the field of view (FOV) was not a problem. The position determined for OO Aql was R.A. (2000.0) $19^h 48^m 12.653^s$ and Dec. (2000.0) $+09° 18' 32.76''$ based upon the reference coordinates in the *MPO Star Catalog*. This agrees within 0.4 arcsec of the computed position generated from the SIMBAD website (ICRS 2000.0 coordinates: $19^h 48^m 12.653^s$ $+09° 18' 32.38''$).

3.2. Photometry

As is necessary with ensemble photometry, every attempt was made to ensure that comparison stars were themselves not variable at least over the observation time span. This was verified prior to accepting data from each session; variability was generally within ±0.03 magnitude. In an attempt to minimize differential refraction and color extinction, only those observations at or above 30° altitude were used to produce the light curve for OO Aql. These readings corresponded to an airmass ranging from 1.18 to 2.0. Plotting the difference in magnitude over time from each comparison star against the averaged magnitude for all other comparisons yielded a narrow range of values with no obvious trend. Representative examples are shown for a dataset collected on September 2, 2005 (Figure 2). There was no evidence that any comparison star exhibited a pattern that would otherwise suggest variability beyond experimental error.

3.3. Ephemeris

A total of 710 individual photometric readings were combined to produce a light curve (Figure 3) that spanned ten weeks of data collection. These observations included 3 minima (Table 1) which were captured over five nights between July 3, 2005, and September 18, 2005. Initially seeded with the orbital period estimate from Hrivnak (1989), the Fourier analysis routine in MPO CANOPUS provided a period solution for the entire dataset. The time of minimum for the latest primary epoch was estimated by CANOPUS using the Hertzsprung method as detailed by Henden and Kaitchuck (1990), and the linear ephemeris equation (1) was determined to be:

$$\text{Min. I (hel.)} = \underset{\pm 0.0009}{2453615.7139} + \underset{\pm 0.00001}{0.50681}\ E \qquad (1)$$

This orbital period compares very favorably with values reported by a number of investigators including Kwee (1958), Binnendijk (1968), Demircan and Güdür (1981), Rudnicki (1982), and Lafta and Grainger (1985).

The three new minima along with additional values from Kim *et al.* (2006), Biró *et al.* (2006) and Hübscher *et al.* (2005) were entered into the OO Aql "Eclipsing Binary O–C" EXCEL spreadsheet file developed by Nelson (2005). The reference epoch from the *General Catalogue of Variable Stars* (Kholopov *et al.* 1985) was used to calculate O–C residuals and was defined by the following linear ephemeris equation (2):

$$\text{Min. I (hel.)} = 2438613.2222 + 0.5067884\ E \qquad (2)$$

Epochs prior to July 2, 1995, were not plotted in order to focus on behavior of the system over the past decade (Figure 4). To determine the error terms for slope and intercept, these data were also evaluated by the regression data analysis tool in EXCEL. Figure 4 shows two discrete linear least squares fits which divide the data over the past decade. A point of inflection is observed in the 1999 data cluster centered near cycle 25320. Times of minima starting with cycle 25782 (May 15, 2000) begin a trend upward which potentially signals an increase in period. This directional change is confirmed with the next four times of minima (ToM) which are centered around cycle 26690. Therefore, by no later than May 15, 2000, a shift to a new and longer orbital period for OO Aql had most likely occurred. A revised linear ephemeris equation (3) based upon O–C data starting with cycle number 25782 was calculated:

$$\text{Min. I (hel.)} = \underset{\pm 0.0073}{2438613.1037} + \underset{\pm 0.0000003}{0.5067936}\ E \qquad (3)$$

This behavior is consistent with preceding epochs in which the orbital period of OO Aql shifted from one constant value to another, as opposed to a continuously-varying period (Hrivnak 1989). Lafta and Grainger (1985) had suggested that period fluctuations may result from a third body or nodal regression, however, it is now well established that the orbital path for each component in OO Aql is circular and that no evidence exists for the presence of a third body close enough to gravitationally influence this binary system. In a recent study by Borkovits *et al.* (2005), Fourier analysis uncovered evidence for two fundamental periods for OO Aql between July 3, 1932, and June 20, 2003. These included the first harmonic for long period (~75 years) sinusoidal change as well as one for short period (~20.25 years) fluctuations. Should these predictions prove accurate, OO Aql has recently entered into a more than 37-year era in which the orbital period will generally be increasing. Whether this is statistical chance or a fundamental change in the physical characteristics of this binary system is worth further investigation.

4. Conclusions

Clear filter CCD photometric readings have led to the construction of a light curve which has been used to revise the orbital period for OO Aql and calculate an updated linear ephemeris (Min. I (hel.) = 2438613.1037 ± 0.0073 + 0.5067936 ± 0.0000003 E). The straight but upwardly sloped line for O–C residuals since May 2000 suggests that the orbital period of OO Aql increased around that time but has remained stable over the past five years.

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Table 1. Times of minimum of OO Aquilae.

Computed Time of Minimum (HJD–2400000.0)	*UT Date of Observations*	*Number of Observations*	*Type of Minimum*
53607.6051 ± 0.0004	August 25, 2005	163	I
53615.7139 ± 0.0009	September 2, 2005	149	I
53622.5555 ± 0.0001	September 9, 2005	168	II

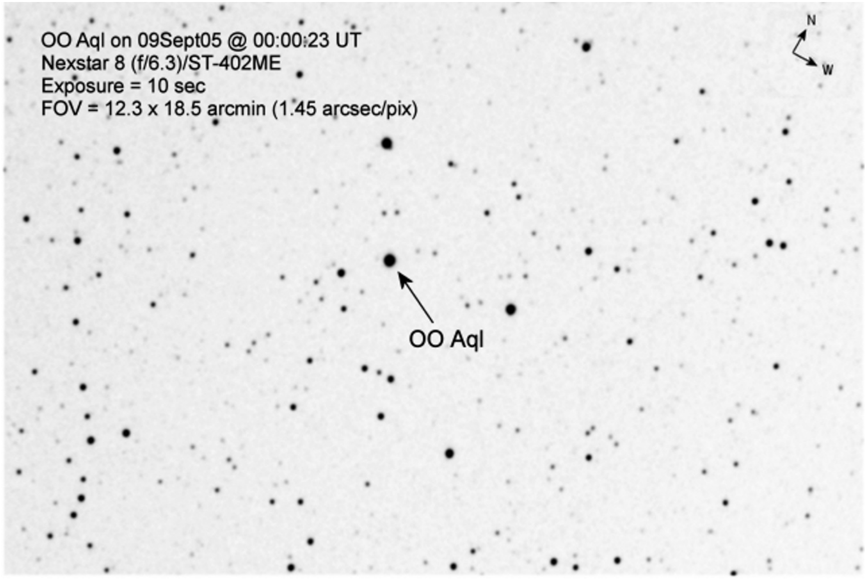

Figure 1. Typical dark and flat field corrected CCD (clear filter) image of OO Aquilae.

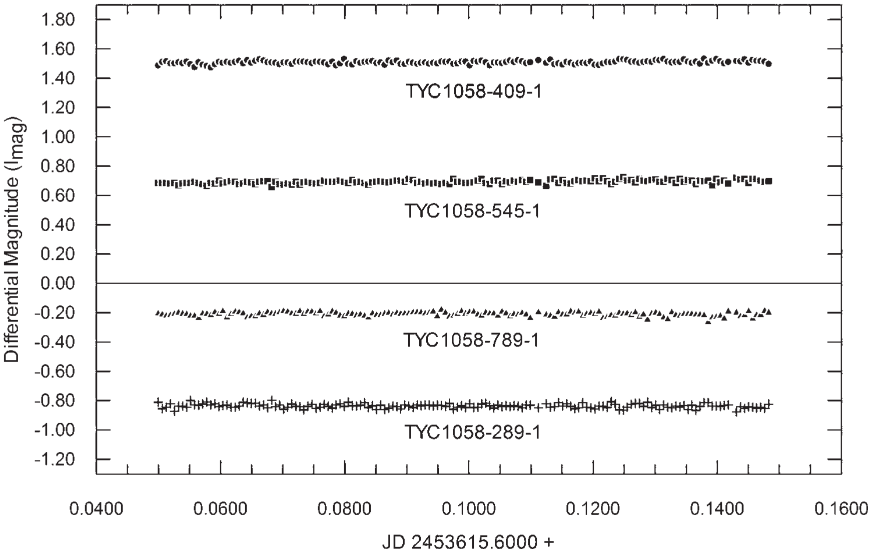

Figure 2. Differential magnitude versus Julian Date for each of four comparison stars calculated from the average instrumental magnitude of the remaining three. These four stars are common to all sessions and remained constant within ±0.03 magnitude.

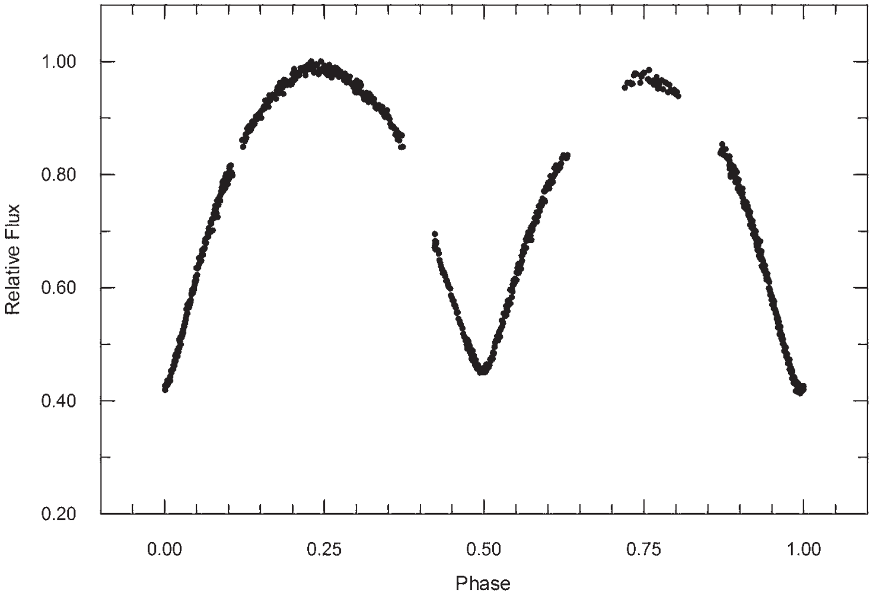

Figure 3. CCD (clear filter) light curve for OO Aql for July–September 2005. Fourier analysis derived period = 0.50681d ±0.00001d.

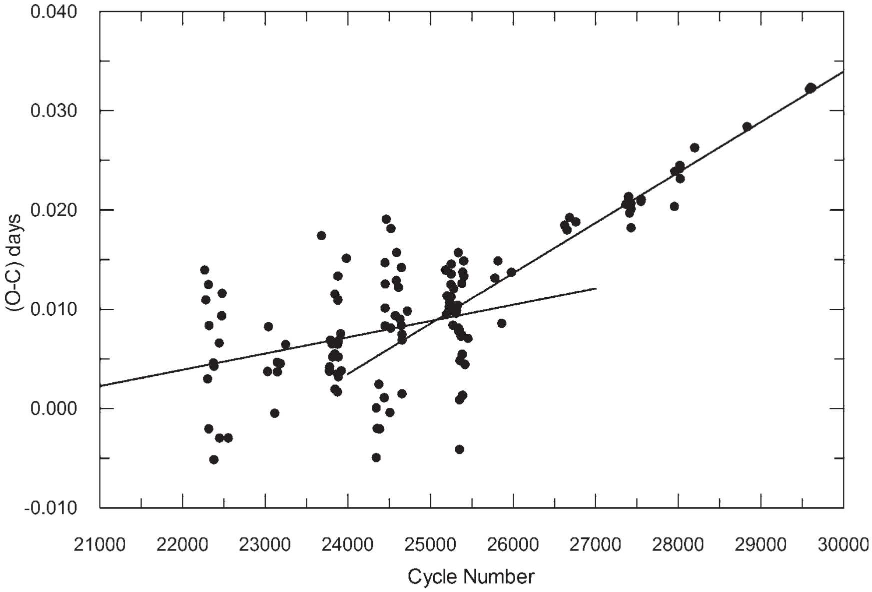

Figure 4. O–C diagram of minima for OO Aql for July 1995–September 2005. Adapted from R. Nelson data at AAVSO website (http://www.aavso.org/observing/programs/eclipser/omc/nelson_omc.shtml).