A Photometric Study of the Misclassified Variable AK Ursae Minoris

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Abstract   The star AK UMi [GSC 4656-0461] was originally misidentified as an RRc-Lyrae pulsating variable by analyzing undersampled survey data. We used greater time resolved differential photometry to positively identify this variable as a W UMa overcontact (subtype A) binary system. The secondary minimum is a total eclipse, which enabled us to approximate the model for this system using some well-known characteristics of overcontact binaries. Our model solution parameters were found to be: $i = 90°$, $q = 0.21$ (M_2/M_1), and $T_1 = 6750K$, which indicated that the primary should be an F4.

1. Introduction

Recent variable star surveys, such as the Northern Sky Variability Survey (NSVS; Wozniak *et al.* 2004) and the All-Sky Automated Survey (ASAS; Pojmański *et al.* 2013), have provided the astronomical community with a wealth of variable star discoveries. The availability of the data has led to independent groups using data mining techniques in an attempt to extract more variable star discoveries. Unfortunately, sampling rates from many of the surveys lack the time resolution to properly identify the nature of the variability of systems with P < 1 day. This can lead to some confusion between light curves of similar profiles, especially those systems that exhibit symmetry. Distinguishing between RRc-Lyrae stars and contact binaries (both A and W subtypes) can be difficult when the sampling rate is inadequate. W Ursae Majoris binaries are further subdivided into two subtypes: the W-type and the A-type. In the W-type, the primary star is the smaller and more compact component. These systems are less massive with short periods, between 0.2 and 0.4 day, with spectral types from G to K. The A-type systems have a smaller and less massive secondary component. In these larger-mass systems the spectral types are A to F with longer periods ranging from 0.4 to 0.8 day (Binnendijk 1965).

GSC 4656-0461 (R.A. 19^h 40^m 41.5^s, Dec. +86° 21' 10.4" (J2000.0)), also recently named AK UMi (Kazarovets *et al.* 2013), was identified as an RRc-Lyrae type variable by Otero (2007) using data from the NSVS imported into a period analyzing software, known as AVE (Analysis of Stellar Variability) (Bareberá 1996), that utilizes a user-defined period range along with an algorithm to search for the best possible solution. More recently, Hoffman *et al.* (2009) used Fourier coefficients which resulted in their conclusion that AK UMi may be a W UMa eclipsing binary. However, the light curve generated by the NSVS data used by Otero (2007) to support their claim was compiled using only 104 NSVS observations that were made over a 260-day time span, equivalent to an average sampling rate of 0.4 obs/day. The symmetrical shape of the light curve from the original discovery paper has led to this photometric campaign to definitively identify the type of variability. We were able to gather much more data than available in the original discovery paper and therefore come to a more conclusive, and very different, supposition about the nature of the variability of AK UMi.

2. Observations

Differential photometry was performed on AK UMi using the 0.6-m Cassegrain telescope atop the Math and Science Center at Emory University. Data were collected on the evenings of December 2, 13, and 22, 2012, using an Apogee Alta U47 at f/8. To achieve the best time resolution possible and the highest SNRs, we chose to image through a Johnson R filter for the entire observing campaign. Since AK UMi is circumpolar, we were able to acquire images for each entire night through air masses that ranged only between 1.16 and 1.26, and a total of 1,537 high-quality images were taken over the three nights. Figure 1 shows the field of view. The designations for the comparison stars that were used are listed in Table 1, along with their (J2000.0) coordinates provided by SKY6 Planetarium Software (Software Bisque 2015).

All of the images were calibrated through MAXIMDL (Diffraction Limited 2012) using biases, darks, and flats.

Table 1. Comparison stars used for AK UMi.

Star	Catalog Number	R.A. (J2000.0) h m s	Dec. (J2000.0) ° ' "
Reference 1	GSC 4656-0288	19 40 45	+86 22 27
Check 1	GSC 4656-0453	19 45 08	+86 16 15
Check 2	GSC 4656-0260	19 46 19	+86 17 08

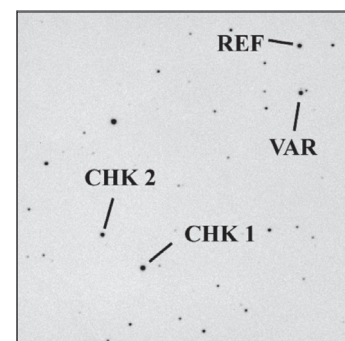Figure 1. Field of View 9.5' × 9.5'. VAR is the target star, AK UMi. One potential third light component can be seen close on the right of VAR.

The two check stars showed no short-term variability during our observations with standard deviations averaging 0.007 magnitude over all three nights. Figure 1 shows the target star with another star nearby that could potentially contaminate the photometry, so a photometric aperture was chosen in an attempt to exclude this source but still allow for accurate measurements. Note that there is a second nearby star that does not show in Figure 1.

3. Light curves and analysis

The light curves from the nights of December 2, 13, and 22 were imported into the period analysis software PERANSO (Vanmunster 2013) and HJD corrected with times of minimum (shown in Table 2) extracted using the extremum tool (Kwee and van Woerden 1956). The final phased light curve is shown in Figure 2. The period found for this variable was 0.536608 day (±0.000154) with an overall Δm of 0.3R. The minimum timing for what appeared to be a primary eclipse was used to establish the following ephemeris (Equation 1).

$$T_{pri} (HJD) = 2456275.765569 + 0.536608 \times E \qquad (1)$$

This phased light curve shows the distinctive characteristics of a W UMa-type eclipsing binary of subtype A, as evidenced by the distinct total eclipse that occurs at the secondary minimum. The period-color relation established by Eggen (1961), and more recently by Wang (1994) and Gazeas and Stępień (2008) (Equation 2), was used to estimate the temperature of the system for modeling purposes.

$$(B–V)_0 = 0.062 – 1.31 \log_{10} P \qquad (2)$$

The orbital period of 0.536608±0.000154 day yields a $(B–V)_0$ value of +0.416, which was used to interpolate an effective temperature from the standard tables found in *Allen's Astrophysical Quantities* (Drilling and Landolt 2000). The implied effective temperature of 6750K corresponds to a spectral type of approximately F4. The masses were estimated using the period-mass equations (Equations 3 and 4) derived

Table 2. Minimum timings of AK UMi.

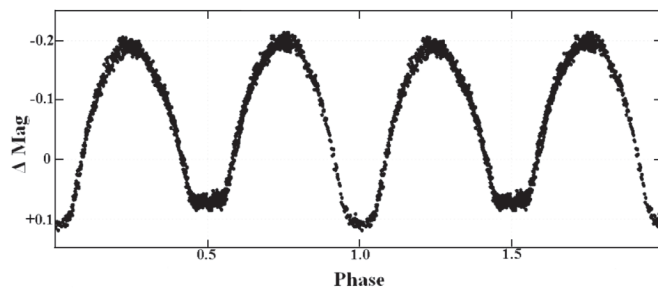| $2450000 + HJD$	Error (10^{-4} days)	Eclipse
6264.766666	±0.66	Secondary
6275.765539	±1.28	Primary
6284.617772	±1.12	Secondary

Figure 2. AK UMi phased light curve. The Δ Magnitude shown is the Johnson R magnitude difference from the reference star.

by Gazeas and Stępień (2008). This allowed the masses to be constrained to a smaller range of values for purposes of modeling.

$$\log M_1 = (0.755 \pm 0.059) \log P + (0.416 \pm 0.024) \qquad (3)$$

$$\log M_2 = (0.352 \pm 0.166) \log P – (0.262 \pm 0.067) \qquad (4)$$

Using the established period and the limits given in Equations 3 and 4, we determined that the initial range of values for the mass ratio (M_2/M_1) should be $0.19 < q < 0.38$.

4. Modeling

Once a suitable range for the mass ratio (q) and temperature was determined, BINARY MAKER (Bradstreet and Steelman 2004) was employed to solve a first order approximation by adjusting the system parameters until a minimum residual value was obtained. Since the temperature of the system was estimated to be less than 7200K, the gravity brightening coefficients were set to the standard value of 0.32, which is commonly used for stars with convective envelopes (Lucy 1967; Rucinski 1973). Gravity brightening refers to a phenomenon in which the poles of a star are brightened due to a higher surface gravity, and, therefore, higher effective temperature, which results from rapid rotation that causes the star to be oblate in shape. BINARY MAKER uses this coefficient in its calculation of local temperature, as the local emergent flux of a star is directly proportional to its local gravity and, therefore, the gravity coefficient (Bradstreet 2005). The primary star was set to the interpolated value of 6750K, and the secondary star was adjusted to achieve the correct ratio that fit the data. Since the secondary eclipse here is in totality, the inclination of the system will be kept at a value of 90°. Limb darkening coefficients were derived from Van Hamme (1993). Limb darkening, an optical effect in which an observer witnesses a diminishment in brightness of a star when looking toward the edge of its disk as opposed to its center, is a function of the gravity coefficient. BINARY MAKER uses the linear limb darkening law (Bradstreet 2005). We set the reflection coefficient to 0.5, as suggested by Rucinski (1969) for binary systems with convective envelopes. The reflection coefficient, also referred to as the "bolometric albedo," represents the percentage of radiation from one member that is absorbed and re-emitted by the companion star (Bradstreet 2005).

The very first attempts for solving the mass ratio made it obvious that a third light component was needed for any reasonable fit to the data. The third light component is a background star that is not part of the AK UMi system and contributes a source of light that cannot be accounted for by examining either member of the binary. The third light parameter in BINARY MAKER is a function of flux (Bradstreet 2005). After a considerable amount of trial and error, a value of $L_3 = 0.36$ was determined to be the best solution. Comparing the residual calculations for mass ratios $0.19 < q < 0.38$, the mass ratio was found to be approximately q = 0.21, meaning the primary star is approximately 5 times more massive than the secondary. Further improvements to the residuals were made by adjusting the fillout factors, measurements of the degree of contact between the stars, which were initially set to 0.15.

Table 3. Solution Parameters for AK UMi.

Parameter	Symbol	Value
Period (days)	P	0.536608
Mass Ratio	M_0/M_1	0.21
Third Light	L_3	0.36
Gravity Coefficient 1, 2	$g_{1,2}$	0.32
Limb Darkening 1, 2	$l_{1,2}$	0.478
Reflection 1, 2	$R_{1,2}$	0.5
Inclination (°)	i	~90
Temperature 1 (K)	T_1	6750
Temperature 2 (K)	T_2	6650
Fillout 1, 2	f	0.6

For an overcontact system in Binary Maker, the fillout factor $(0 < f < 1)$ represents the percentage that the surface potential of the binary lies from the inner critical surface compared to the outer one (Bradstreet 2005). The parameters of the best-fit model from Binary Maker can be found in Table 3.

The relative depths of the eclipses are indicative of overcontact binaries in which the two components are nearly in thermal equilibrium with only a 100K difference. BINARY MAKER only allows for modeling the mean surface effective temperatures of the independent members of the binary and disregards any temperature gradient in their shared convective envelope (Bradstreet 2005). The discovery of the total secondary eclipse has provided a means of computing reasonable first order approximations for the system parameters that would have been otherwise difficult without obtaining radial velocity measurements. The brightness maximums at $\phi = 0.25$ and $\phi = 0.75$ differ slightly in magnitude, where one is brighter than the other. The observation of uneven heights in the two maxima that occur outside of eclipse, known as the O'Connell effect, is likely caused by spot activity in this case (Milone 1968). It would, therefore, also be possible to obtain a slightly better fit to the shoulders of the light curve by the addition of a spot or two. However, since the O'Connell effect is more prevalent at shorter wavelengths and less obvious through an R filter, a full BVR observing campaign would be needed before attempting any valid spot modeling.

5. Conclusion

The variable AK UMi has been positively identified by this campaign as a W UMa overcontact binary system of subtype A and not an RRc-Lyrae star. The use of adequate sampling rates has allowed for more details to emerge that would not have been detected by other surveys such as the NSVS and ASAS.

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