Multiband CCD Photometry of CY Aquarii using the AAVSOnet

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Abstract δ Scuti stars are a class of short-period pulsating variable stars that include CY Aquarii. Multiband CCD photometry was performed on that star using instruments in Massachusetts, New Mexico, and Australia from the AAVSO's global robotic telescope network (AAVSOnet). Rapid cadence, multi-hour time series yielded high precision light curves and 21 new maxima. Data analyses revealed a pulsation pattern consistent with the existing model that describes the origin of SXPHE stars.

1. Introduction

1.1. DSCT

δ Scuti Stars (DSCT) are a diverse class of very short period variables. Some have amplitudes of nearly one magnitude and regular light curves while others have complex light curves with multiple periods and millimagnitude light variations. These stars pulsate radially (and sometimes non-radially) and lie just above or on the main sequence of the Hertzsprung-Russell (H-R) diagram between approximate spectral types A7-F2. The pure non-radial pulsators are called γ Doradus stars and are separate from the DSCTs.

1.2. HADS

The High Amplitude δ Scuti stars (HADS) are a subset of the DSCTs. They are highly evolved pulsating variable stars with amplitudes above 0.1 in V residing well off the main sequence in the sub-giant branch of the H-R diagram. These Population I stars pulsate in a single radial manner and exhibit a period-luminosity relationship (Templeton 2005).

1.3. SXPHE

SX Phoenicis stars (SXPHE), by contrast, are Population II stars which exhibit light curves that closely resemble the HADS. Some SXPHE stars pulsate in one mode and others in two. SXPHE stars tend to be located in globular star clusters or the galactic halo and also exhibit a period-luminosity relationship. Long-term period changes have been noted in these stars which exceed the expected rates from stellar evolution (Handler 2000). The cause of these changes is not generally understood.

Blue straggler stars are believed to increase in mass and luminosity late in life due to interactions with nearby stars in globular clusters or from binary companions. The period ratios of SXPHE stars that pulsate in two modes indicate a greater than expected mass suggestive of a similar mechanism to that which is seen with the blue stragglers (Percy 2007).

1.4. CY Aqr

CY Aquarii (CY Aqr) is an SXPHE star which had the shortest period of any known variable at the time of its discovery by Hoffmeister (1934). The AAVSO's Variable Star Index (VSX; Watson *et al.* 2014) currently lists its period at 0.061038408 day. CY Aqr has a V magnitude of 10.42–11.20

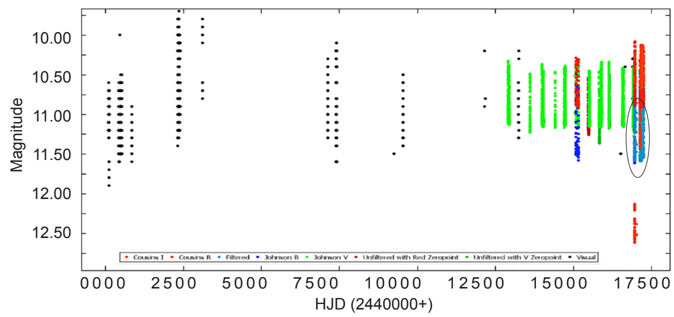

Figure 1. Total AID light curve for CY Aqr. Filtered AAVSOnet data are circled lighter points.

and an epoch 2000 declination of approximately +01^h 32^m. It is therefore well positioned in the sky for observations done in temperate zones both north and south of the equator using small- aperture instruments. It is not associated with a star cluster and therefore unlikely to be affected by the interactions that are seen with blue stragglers. Observations of this star since 1960 have been recorded in the AAVSO International Database (AID; AAVSO 2015) and are shown in Figure 1.

The most recent study of this star (Sterken *et al.* 2011) yielded twenty-nine new maxima based upon more than a dozen partial nights of filterless CCD photometry combined with photomultiplier photometry.

1.5. AAVSOnet

The AAVSO has established a global robotic telescope network. A subgroup of the AAVSOnet instruments are the Bright Star Monitors (BSMs). These are small refractors which provide low resolution but wide field images that are well suited to un-crowded star fields with stars of magnitude 2–12 (Henden 2014). They also work well in light polluted areas. CY Aqr is bright and not in a crowded star field, making it appropriate for study with the BSMs.

2. Methods

2.1. Instrumentation and observations

CCD photometry data were obtained for CY Aqr using the BSM-HQ (Massachusetts), BSM-NM (New Mexico), and BSM-S (Australia). Each instrument performed multi-hour time series with a cadence of approximately six minutes in four different band passes (Johnson B and V, Cousins R and I) from October 2014 through August 2015. Exposure times were 30s in R and I, 40s in V, and 80s in B. This yielded a total of 1975 usable images over 22 nights. All images were calibrated and air-mass corrected. Due to technical issues with the AAVSOnet's executive software, only some of the data could be transformed. All data were submitted to the AAVSO International Database (AID). Due to the low density of observations (see Figure 3), the times of maximum light and period calculations were determined by visual inspection.

2.2. Mathematical analysis

Epoch: HJD 2454562.14017 analyses were performed using AAVSO's VPHOT (AAVSO 2012) and VSTAR (Benn 2013) software programs.

3. Results

3.1. Light curves

A illustrative image of CY Aqr is shown in Figure 2. The B, V, R, and I light curves from a representative BSM-S time series are provided in Figure 3.

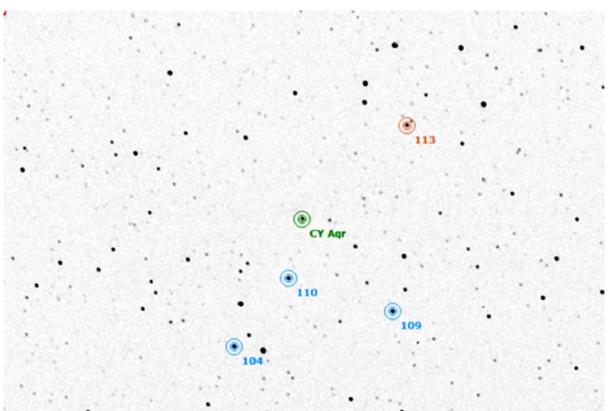

Figure 2. CY Aqr CCD field. South is up and West is left. Field of view 2.40º × 1.30º. Target is CY Aqr; comparison stars are 10.4, 10.9, and 11.0; and check star is 11.3.

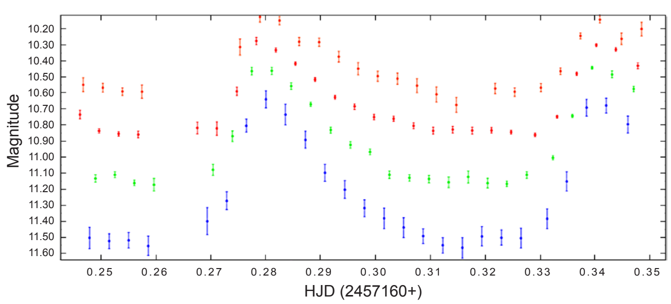

Figure 3. Time Series light curves for CY Aqr showing maxima at HJD 2457160.278 and 2457160.340. Mean Error bars denote 95% confidence intervals (twice Standard Error). Curves are, from top to bottom: Cousins I, Cousins R, Johnson V, Johnson B.

3.2. Phase plot

The phase plot reduced to the sun with Fourier model and residuals for all AAVSOnet V-band data is shown in Figure 4 and is consistent with a single pulsation mode. Higher order

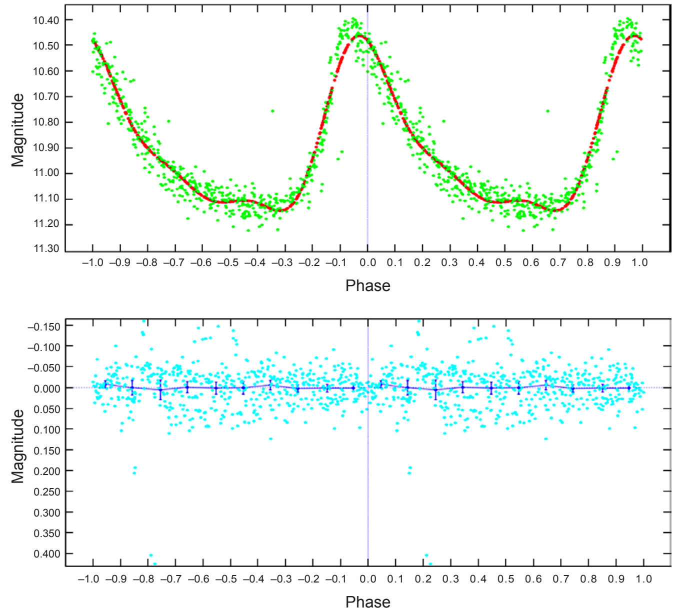

Figure 4. Phase Plot for CY Aqr of all V-Band AAVSOnet data. Period, 0.061038 d; epoch, HJD 2454562.14017. Model (top plot; points are Johnson V, line denotes model) and Residuals (bottom plot; points denote residuals, line with error bars are the means).

harmonics did not improve the model although it imprecisely fits the observations around the time of maximum light.

Based upon the p-value of 0.973829 for the residuals, the null hypothesis is assumed to be true and it is highly unlikely that there is additional periodicity not captured by the model. The Fourier expression is shown in Equation 1.

$$
\begin{aligned}
f(t) &= 11.13841 \\
&+0.315658\times\cos(2\pi 1(t-2457134.6))+0.096227\times\sin(2\pi 1(t-2457134.6)) \\
&-0.017152\times\cos(2\pi 2(t-2457134.6))+0.005503\times\sin(2\pi 2(t-2457134.6)) \\
&-0.269837\times\cos(2\pi 3(t-2457134.6))-0.180788\times\sin(2\pi 3(t-2457134.6)) \\
&-0.253838\times\cos(2\pi 4(t-2457134.6))-0.30852\times\sin(2\pi 4(t-2457134.6)) \\
&-0.086311\times\cos(2\pi 5(t-2457134.6))-0.168185\times\sin(2\pi 5(t-2457134.6)) \\
&+0.02972\times\cos(2\pi 6(t-2457134.6))+0.085495\times\sin(2\pi 6(t-2457134.6)) \\
&-0.016844\times\cos(2\pi 7(t-2457134.6))+0.284924\times\sin(2\pi 7(t-2457134.6)) \\
&-0.118102\times\cos(2\pi 8(t-2457134.6))+0.31447\times\sin(2\pi 8(t-2457134.6)) \\
&-0.176364\times\cos(2\pi 9(t-2457134.6))+0.214283\times\sin(2\pi 9(t-2457134.6)) \\
&-0.081207\times\cos(2\pi 10(t-2457134.6))+0.056482\times\sin(2\pi 10(t-2457134.6))
\end{aligned}
\tag{1}
$$

3.3. Ephemeris and period analysis

Twenty-one new maxima were determined from the AAVSOnet data set and are shown in Table 1. The calculated times of maxima were derived from Equation 2 where E is the cycle number. Extrapolating by inspection from the ephemeris of Sterken *et al.* (2011), O–C should be gradually declining from approximately 0.01 to –0.01 between October 2014 and August 2015. The AAVSOnet data set for CY Aqr appears to behave in accordance with that pattern.

$$T_{max} = 2426159.5132 + (0.0610)(E) \tag{2}$$

For those time series that contained at least two maxima or minima, period calculations were obtained and are displayed

Table 1. Times of Maximum Light (T_{max}) Observed (O), Calculated (C), and cycle number (E) for CY Aqr (HJD 2450000+) from the AAVSOnet data set.

$T_{max}(O)$ (HJD 2450000+)	E	$T_{max}(C)$ (HJD 2450000+)	O–C
6960.933	504941	6960.914	0.019
6960.990	504942	6960.975	0.015
6961.054	504943	6961.036	0.018
7160.278	508209	7160.662	0.016
7160.340	508210	7160.323	0.017
7168.213	508339	7168.192	0.021
7168.278	508340	7168.253	0.025
7168.336	508341	7168.342	–0.006
7188.176	508667	7188.200	–0.024
7188.237	508668	7188.261	–0.024
7195.256	508783	7195.276	–0.020
7195.317	508784	7195.337	–0.020
7211.125	509043	7211.362	–0.237
7211.186	509044	7211.197	–0.011
7221.248	509209	7221.262	–0.014
7222.844	509235	7222.848	–0.004
7222.905	509236	7222.909	–0.004
7223.089	509239	7223.092	–0.003
7223.150	509240	7223.153	–0.003
7223.209	509241	7223.214	–0.005
7223.271	509242	7223.275	–0.004

Table 2. Period analysis for CY Aqr from the AAVSOnet data set.

Interval (HJD 2450000+)	Period (days)
6960.933–6961.054	0.0616
7160.278–7160.340	0.0620
7168.213–7168.336	0.0615
7188.176–7188.237	0.0608
7195.256–7195.317	0.0609
7211.125–7221.248	0.0616
7222.844–7222.905	0.0611
7223.089–7223.271	0.0604

in Table 2. Based principally upon the ephemeris in Table 1, there appears to be no significant changes in the period of this star between October 2014 and August 2015.

4. Discussion

The CY Aqr data provide a striking paradox. HADS, at approximately two solar masses, are sufficiently massive that they should be expected to have remained in the main sequence for only about one billion years. Yet the SXPHE, of similar mass (Andreasen 1983), are Population II stars and therefore about as old as the universe. They should have evolved into white dwarfs and become silent many billions of years ago. However, they clearly continue to pulsate with a primary radial mode closely resembling the HADS.

A binary model with a highly eccentric orbit has been proposed by Fu and Sterken (2003). Thus two ancient Population II white dwarf stars each about as massive as the sun would have merged about one billion years ago. This combination star would have re-ignited and then recently left the main sequence. It now behaves like a typical HADS. This model, however, does not account fully for all data, including the long-term period changes. Further observations to include new times of maxima will be required for a complete solution.

5. Acknowledgements

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