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Discovery of optical flickering from the symbiotic star EF Aquilae

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We report optical charge-coupled device (CCD) photometry of the recently identified symbiotic star EF Aquilae (EF Aql). Our observations in the Johnson V and B bands clearly show the presence of stochastic light variations with an amplitude of about 0.2 mag on a time scale of minutes. The observations point toward a white dwarf (WD) as the hot component in the system. It is the 11th object among more than 200 symbiotic stars known with detected optical flickering. Estimates of the mass accretion rate onto the WD and the mass loss rate in the wind of the Mira secondary star lead to the conclusion that less than 1% of the wind is captured by the WD. Eight further candidates for the detection of flickering in similar systems are suggested.

KEYWORDS
stars: binaries: symbiotic – white dwarf – accretion, accretion discs– stars: individual: EF Aql

1 | INTRODUCTION

EF Aquilae (EF Aql) was identified as a variable star on photographic plates from the Königstuhl Observatory (Reinmuth 1925). Richwine et al. (2005) have examined the optical survey data for EF Aql and classified it as a Mira-type variable with a period of 329.4 days and amplitude of variability >2.4 mag. Recently, Margon et al. (2016) reported that the optical spectrum shows prominent Balmer emission lines visible through at least H11 and [*O III*] λ5007 emission. These emission lines and the bright ultraviolet (UV) flux detected in Galaxy Evolution Explorer (GALEX) satellite images provide undoubted evidence for the presence of a hot companion. Thus EF Aql is classified as a symbiotic star, a member of the symbiotic Mira subgroup (Margon et al. 2016).

Symbiotic stars are long-period interacting binaries, consisting of an evolved giant transferring mass to a hot compact object. Their orbital periods are in the range 100 days to more than 100 years. A cool giant or supergiant of spectral class G-K-M is the mass donor. If this giant has Mira-type variability, the system usually is a strong infrared source. The hot secondary accretes material supplied from the red giant. In most symbiotic stars, the secondary is a degenerate star, typically a white dwarf (WD) or subdwarf (Mikołajewska 2003). In a few cases, the secondary has been shown to be a neutron star (e.g., Davidsen et al. 1977; Kuranov & Postnov 2015; and references therein).

Systematic searches for flickering variability in symbiotic stars and related objects (Angeloni et al. 2012, 2013; Dobrzycka et al. 1996; Gromadzki et al. 2006; Sokoloski et al. 2001; Stoyanov 2012) have shown that, among the more than 200 symbiotic stars known, only in 10 objects flickering activity is detected: that is, RS Oph, T CrB, MWC 560, Z And, V2116 Oph, CH Cyg, RT Cru, *o* Cet, V407 Cyg, and V648 Car.

Here we report optical charge-coupled device (CCD) photometry of EF Aql and the detection of flickering in the Johnson V and B bands.

2 | OBSERVATIONS

During the period August–November 2016, we secured CCD photometric monitoring with five telescopes equipped with CCD cameras:

- the 2.0-m RCC telescope of the National Astronomical Observatory Rozhen, Bulgaria (CCD VersArray 1300 B, $1,340 \times 1,300$ px);
- the 50/70-cm Schmidt telescope of NAO Rozhen (SBIG STL11000M CCD, $4,008 \times 2,672$ px);
- the 60-cm telescope of the Belogradchick Astronomical Observatory (SBIG ST8 CCD, $1,530 \times 1,020$ px);
- the 30-cm astrograph of IRIDA Observatory (CCD camera ATIK 4000M, $2,048 \times 2,048$ px);
- the automated 41-cm telescope of the University of Jaén, Spain—ST10-XME CCD camera with $2,184 \times 1,472$ px (Martí et al. 2017).

All the CCD images were bias-subtracted and flat-fielded, and standard aperture photometry was performed. The data reduction and aperture photometry were done with IRAF and checked with alternative software packages. A few objects from the APASS catalog (Henden et al. 2016; Munari et al. 2014) have been used as comparison stars. As check stars, we used USNO U0825.17150321, USNO U0825.17161750, and USNO U0825.17157668. In Figure 1 and Table 2, they are marked as check-1, check-2, and check-3, respectively.

The results of our observations are summarized in Table 1 and plotted in Figure 1. For each run, we measures the minimum, maximum, and average brightness in the corresponding band, plus the standard deviation of the run. For each run, we calculate the root mean square (rms) deviation

$$\sigma_{\rm rms} = \sqrt{\frac{1}{N_{\rm pts}} \sum_i (m_i - \overline{m})^2}, \qquad (1)$$

where $\overline{m}$ is the average magnitude in the run. $\sigma_{\rm rms}$ calculated in this way includes the contributions from the variability of the star (if it exists) and from the measurement errors. For nonvariable stars, it is a measure of the accuracy of the photometry.

3 | DETECTION OF FLICKERING IN EF AQL

During our observations, the V-band brightness of EF Aql was in the range $15.1 \leq V \leq 16.03$. The General Catalogue of Variable Stars (Samus et al. 2017) suggests brightness of EF Aql in the range $12.4 \leq V \leq 15.5$. The All Sky Automated Survey (ASAS) data (Pojmanski & Maciejewski 2004) show variability in the range $12.5 \leq V \leq 16.0$. The lowest brightness in our set is $V \approx 16.03$, which is about the minimum brightness measured in ASAS, indicating that our observations are near the minimum of the Mira cycle.

Rapid, aperiodic brightness variations, like the flickering from cataclysmic variables (Bruch 2000; Warner 1995), is evident on all our observations in B and V bands. It is not detectable in the I band, suggesting that the I flux is dominated by the red component. Figure 1 shows the light curves from three observations. For comparison, two check stars (one brighter than EF Aql, and one fainter) are also plotted on the same scale. It is apparent that the variability of EF Aql is considerably larger than that of the check stars, which indicates that it is not a result of observational errors.

The $\sigma_{\rm rms}$ expected from the accuracy of the photometry can be deduced from the observations of the check stars with brightness similar to that of EF Aql. In Table 1 we give the mean magnitude and $\sigma_{\rm rms}$ of EF Aql and the three check stars. The rms deviation $\sigma_{\rm rms}$ of EF Aql exceeded that expected from the check star by more than a factor of two.

In Figure 2 we plot σ_{rms} for EF Aql and of about 30 other stars from the field around EF Aql. During run 20160828 (plotted with plus signs), EF Aql exhibits flickering with peak-to-peak amplitude 0.16 mag. The rms deviation is $\sigma_{rms}(EFAql) = 0.033$ mag. For stars with similar brightness, we have $\sigma_{\rm rms} \approx 0.009$ mag. In other words, $\sigma_{\rm rms}$ of EF Aql is more than 3 times larger than expected from observational errors. During run 20161102, EF Aql exhibits flickering with higher amplitude of about 0.30 mag. The rms variability is $\sigma_{\rm rms}(EFAql) = 0.061$ mag. For stars with similar brightness, we have $\sigma_{\rm rms} \approx 0.008$ mag. In other words, the rms of EF Aql is more than 7 times larger than that expected from observational errors.

Using our simultaneous B- and V-band observations obtained on August 28, 2016 (see Table 1) and interstellar extinction $A_{\rm V} = 0.45$ (Margon et al. 2016), we calculated the dereddened color of the flickering source as $(B-V)_0 = 0.35 \pm 0.05$. For comparison, the average $(B-V)_0$ color of the flickering source is 0.25 ± 0.21 in the recurrent novae T CrB and RS Oph, and 0.10 ± 0.20 in the cataclysmic variables (Bruch 1992; Zamanov et al. 2015). It appears that $(B-V)_0$ of the flickering source in EF Aql is more similar to the flickering source in T CrB and RS Oph, which also contain a red giant mass donor.

4 | DISCUSSION

From our R- and I-band observations of EF Aql, we measure $(R-I) = 3.08 \pm 0.06$ and $(R-I) = 2.93 \pm 0.05$, for August 28, 2016, and September 4, 2016, respectively. Applying $A_{\rm V} = 0.45$ and the calibration of Fitzpatrick (1999), we correct $(R-I)$ for interstellar reddening, and find $2.78 < (R-I)_0 < 3.04$, which (using the results of Celis 1984) corresponds to a spectral subtype of the asymptotic giant branch star of M7–M8. An asymptotic giant of spectral type M7–M8

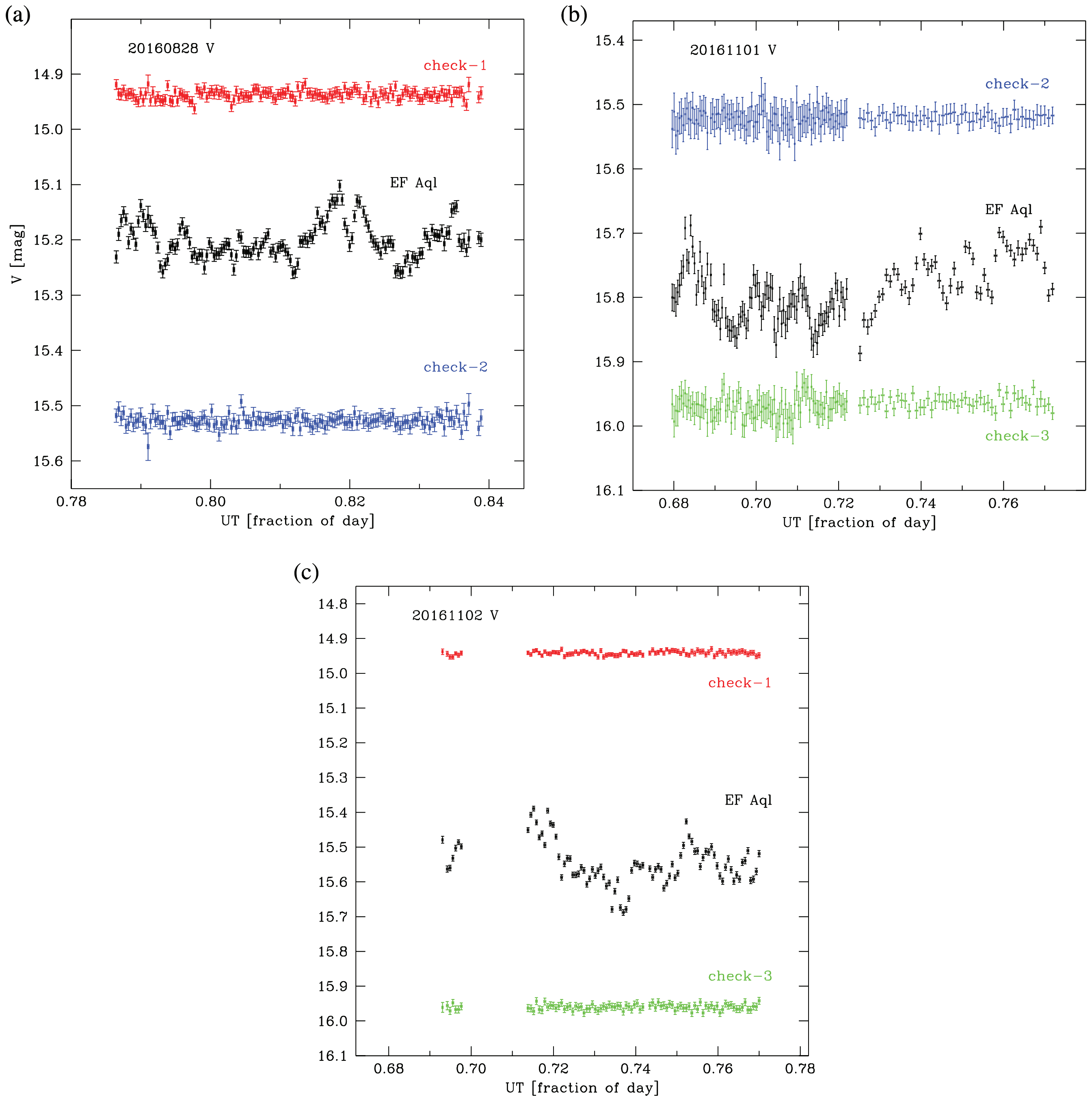

FIGURE 1 Detection of optical flickering of EF Aquilae (EF Aql). In each panel, two check stars are also shown on the same scale. It is clearly seen that EF Aql varies with an amplitude larger than 0.15 mag

is expected to have $(V-R)_0 \approx 4.0$–4.5 (Celis 1982), and we estimated the brightness of the red giant in the V band around the time of our observations (at minimum of the Mira cycle) as $V \sim 17.8$–18.5 mag.

The nonvariable light from the red giant contributes about 20% of the flux at the V band. Figure 1 demonstrates that the V-band flux can change by more than 5% (0.05 mag) in less than 5 min and more than 20% (0.20 mag) in less than 1 hr. Taking into account the contribution of the red giant, these rapid fluctuations correspond to variations of up to ±25% (from the average level) in the V-band flux from the hot component of EF Aql. The brightness fluctuations of EF Aql are similar to those observed in the prototype Mira (omicron Ceti) by Sokoloski & Bildsten (2010).

The flickering (stochastic photometric variations on timescales of a few minutes with amplitude of a few×0.1 mag) is a variability typical for the accreting WDs in cataclysmic variables and recurrent novae. About the nature of the hot companion in EF Aql, Margon et al. (2016) supposed that the hot source is likely more luminous than a WD, and thus may well be a subdwarf. The persistent presence of minute-timescale stochastic optical variations (see Table 1) with the observed amplitude is a strong indicator that the hot component in EF Aql is a WD.

TABLE 1 Charge-coupled device (CCD) observations of EF Aquilae (EF Aql). Shown are the date of observation (in format yyyymmdd), UT-start and UT-end of the run, the telescope, band, exposure time, number of CCD images obtained, minimum–maximum magnitudes in each band, average magnitude in the corresponding band, and typical observational error

Date	UT	Telescope (start–end)	Filter	Exp. time (s)	N_{pts}	Min–max (mag)	Average (mag)	Error(mag)
20160828	18:52–20:11	2.0 m	V	20	146	15.102–15.260	15.201	0.010
20160828	18:53–20:08	50/70 cm	B	120	32	16.053–16.233	16.144	0.020
20160903	19:42–20:55	41 cm Jaen	I	60	36	10.920–10.944	10.932	0.002
20161028	16:27–17:54	60 cm Bel	V	120	40	15.564–16.028	15.773	0.033
20161030	16:06–16:29	2.0 m	V	20	32	15.371–15.473	15.412	0.009
20161101	16:18–18:32	2.0 m	V	20, 60	150	15.690–15.809	15.752	0.010
20161102	16:36–18:29	2.0 m	V	40	90	15.389–15.688	15.546	0.008
20161110	16:49–18:20	30 cm Irida	V	150	33	15.494–15.888	15.705	0.046

TABLE 2 V band observations of EF Aquilae (EF Aql) and the check stars in the field.The average magnitude and σ_{rms} are given for each object

			EF Aql	Check-1	Check-2	Check-3
Date	Telescope	Filter	Mean $\pm$ σ_{rms}	Mean $\pm$ σ_{rms}	Mean $\pm$ σ_{rms}	Mean $\pm$ σ_{rms}
20160828	2.0 m	V	15.201 $\pm$ 0.033	14.937 $\pm$ 0.008	15.527 $\pm$ 0.010	15.964 $\pm$ 0.013
20161028	60 cm Bel	V	15.773 $\pm$ 0.104	14.986 $\pm$ 0.038	15.574 $\pm$ 0.023	16.062 $\pm$ 0.040
20161030	2.0 m	V	15.412 $\pm$ 0.030	14.914 $\pm$ 0.006	15.465 $\pm$ 0.008	15.948 $\pm$ 0.015
20161101	2.0 m	V	15.752 $\pm$ 0.035	14.937 $\pm$ 0.008	15.520 $\pm$ 0.007	15.962 $\pm$ 0.009
20161102	2.0 m	V	15.546 $\pm$ 0.061	14.943 $\pm$ 0.007	15.525 $\pm$ 0.009	15.960 $\pm$ 0.009
20161110	30 cm	V	15.705 $\pm$ 0.094	14.936 $\pm$ 0.033	15.511 $\pm$ 0.034	15.976 $\pm$ 0.060

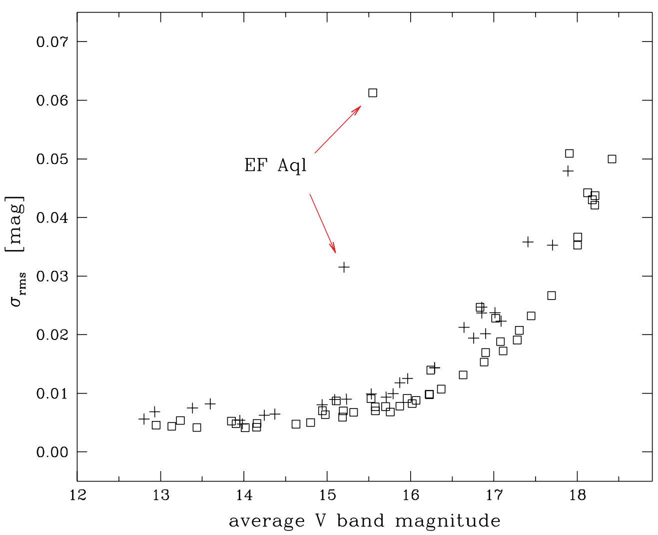

FIGURE 2 Root mean square deviation versus the average V-band magnitude. The plus signs refer to the night 20160828, and the squares to 20161102. In both nights, EF Aql deviates considerably from the behavior of the other stars, which indicates that it is variable during our observations

In Galaxy Evolution Explorer (GALEX) catalogs of ultraviolet (UV) sources (Bianchi et al. 2011), we find FUV and NUV magnitudes of EF Aql (16.797, 16.269), T CrB (16.166, 15.227), RS Oph (16.284, 15.841), AG Dra (12.003, 12.580), and RR Tel (12.428, 13.229). For RS Oph, we adopt $E(B-V) = 0.60$ (e.g., Nelson et al. 2011) and a distance of 1,400 pc (Barry et al. 2008); for T CrB—$E(B-V) = 0.10$ and a distance of 1,020 pc (Harrison et al. 1993); for AG Dra—$E(B-V) = 0.05$, $d = 2{,}500$ pc (Sion et al. 2012); and for RR Tel—$E(B-V) = 0.10$ (Young et al. 2005), $d = 2{,}500$ pc (Kotnik-Karuza et al. 2006). For the interstellar extinction, we apply $A_{FUV} = 8.29 \times E(B-V)$ and $A_{NUV} = 8.18 \times E(B-V)$ (Seibert et al. 2005). We calculate that in the NUV and FUV bands the hot component of EF Aql is about 12–15 times brighter than the WD of T CrB. However, it is 5–6 times fainter than the WD of RS Oph, 5–15 times fainter than the WD of AG Dra, and 5–10 times fainter than the WD of RR Tel. This indicates that the UV brightness of the hot component of EF Aql is similar to that of the WDs in symbiotic stars.

A comparison of the flickering of EF Aql with that of the symbiotic recurrent nova RS Oph (see fig. 1 in Zamanov et al. 2010) shows that in RS Oph the flickering is visible in BVRI bands, while in EF Aql it is not detectable in the I band but clearly visible in B and V bands. In RS Oph, the mass accretion rate is about $\sim 2 \times 10^{-8}$ $M_\odot$ year^{-1} (Nelson et al. 2011). In EF Aql, we see flickering in V, which means that the hot component is brighter than the M giant in the V band. Overall, the relative color dependence of flickering in EF Aql implies that the mass accretion rate is less than that in RS Oph, but not too much lower, probably of a few$\times 10^{-9}$ $M_\odot$ year^{-1}.

Le Bertre et al. (2003) provide K and L′ photometry for EF Aql, and classify it as an oxygen-rich, asymptotic giant branch star located at a distance of $d = 3.5$ kpc and losing mass at a rate 3.8×10^{-7} $M_\odot$ year^{-1}. We used 2MASS $K = 5.36$ mag and IRAS 12-μm flux (4.78 Jy) to estimate the color K-[12] defined by Gromadzki et al. (2009). Then, applying their Equation (4), we determined a mass loss rate of 2×10^{-6} $M_\odot$ year^{-1} for EF Aql. This means that the WD is capturing less than 1% of the stellar wind of the red giant.

In addition to the optical observations presented here, we searched the new gPhoton database (Million et al. 2016) for GALEX ultraviolet observations of EF Aql. gPhoton has a calibration and extraction pipeline that allows easy access to calibrated GALEX data. Using its module gFind, we found five epochs of observations in the NUV band (NUV, 1,771–2,831 Å), only one of which was previously reported by Margon et al. (2016). We then used the gMap and gAperture modules to determine aperture size and background annulus size and positions, to make sure that all the counts were inside the aperture and no contaminating sources were within the background subtraction annulus. We thus obtain the following fluxes:

20040630 17 : 06 $6.25 \pm 0.09 \times 10^{-15}$ erg s^{-1} cm^{-2} Å^{-1},
20050627 14 : 39 $6.64 \pm 0.08 \times 10^{-15}$ erg s^{-1} cm^{-2} Å^{-1},
20100813 16 : 53 $7.98 \pm 0.04 \times 10^{-15}$ erg s^{-1} cm^{-2} Å^{-1},
20100815 09 : 58 $8.26 \pm 0.04 \times 10^{-15}$ erg s^{-1} cm^{-2} Å^{-1},
20100815 13 : 15 $8.37 \pm 0.04 \times 10^{-15}$ erg s^{-1} cm^{-2} Å^{-1},

where the time is given in the format yyyymmdd hh:mm. These results show that the NUV flux of EF Aql in August 2010 was $\approx$ 30% larger than in June 2004, probably indicating a variable mass accretion rate onto the WD.

There are about 30 symbiotic stars classified as symbiotic Miras (Whitelock 2003). We searched in the Catalogue of Symbiotic Stars (Belczyński et al. 2000), for D-type symbiotics with low ionization potential, which are potential candidates for flickering detection. In our opinion, V627 Cas, KM Vel, BI Cru, V704 Cen, Hen 2-139, V347 Nor, WRAY 16-312, and LMC 1 deserve to be searched for flickering near the minima of the Mira brightness cycle.

Symbiotic binaries (especially those with detected rapid variability) have historically revealed remarkable events of acceleration of ejection of collimated outflows (Brocksopp et al. 2004; Crocker et al. 2002; Taylor et al. 1986) although not as powerful as in X-ray binaries and microquasars. Nevertheless, some of their collimated ejecta display a combination of thermal and nonthermal emission mechanisms (Eyres et al. 2009). Inspection of the EF Aql position in the NRAO VLA Sky Survey (NVSS, Condon et al. 1998) reveals no radio source detection with a 3σ upper limit of 1.6 mJy at 20 cm. As a comparison, this upper limit is very similar to the faint source detection of the nearby symbiotic binary system CH Cygni, which appears at a flux density level of 2.9 mJy in the same survey. However, EF Aql is significantly more distant than CH Cygni (at least 15 times) and therefore the lack of detection at the NVSS sensitivity is not surprising. Deeper radio mapping with modern interferometers would thus be desirable. With the similarities between RS Oph and EF Aql noted above, it may be worthwhile looking for possible recurrent nova outbursts of the latter system in archival data, as has been done for other objects (e.g., Schaefer 2010).

5 | CONCLUSIONS

On seven nights during the period August–November 2016, we performed 11.2 hr of photometric observations of the symbiotic Mira EF Aql. We found that EF Aql exhibits short-term optical variability (flickering) on a timescale of minutes. The detected amplitude is about 0.15–0.30 mag in the B and V bands. The rms deviation of EF Aql is 3–7 times larger than that expected from observational errors. The presence of flickering strongly suggests that the hot component is a WD.

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