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### Article

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# Discovery of optical flickering from the symbiotic star EF Aquilae

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We report optical CCD photometry of the recently identified symbiotic star EF Aql. Our observations in 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 as the hot component in the system. It is the 11-th 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.

## 1 Introduction

EF Aquilae was identified as a variable star on photographic plates from Königstuhl Observatory almost a century ago (Reinmuth 1925). It is associated with a bright infrared source – IRAS 19491-0556 / 2MASS J19515172-0548166. 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  $3.8 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$ . Richwine et al. (2005) have examined the optical survey data for EF Aql and classify it as a Mira type variable with a period of 329.4 d and amplitude of variability  $> 2.4$  mag. The optical spectrum shows prominent Balmer emission lines visible through at least H11 and [O III]  $\lambda 5007$  emission. The emission lines and the bright UV flux detected in GALEX satellite images provide undoubted evidence for the presence of a hot companion. Thus EF Aql appears to be a symbiotic star, a member of the symbiotic Mira subgroup (Margon et al. 2016).

The 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 from 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 or subdwarf. In a few cases has the secondary been shown to be a neutron star (e.g. Bahramian et al. 2014; Kuranov & Postnov 2015; and references therein).

Systematic searches for flickering variability in symbiotic stars and related objects (Dobrzycka et al. 1996; Sokolowski, Bildsten & Ho 2001; Gromadzki et al. 2006; Stoyanov 2012; Angeloni et al. 2012, 2013) have shown that optical flickering activity is rarely detectable. Among more than 200 symbiotic stars known, only 10 present flickering – RS Oph, T CrB, MWC 560, Z And, V2116 Oph, CH Cyg, RT Cru, *o* Cet, V407 Cyg, and V648 Car.

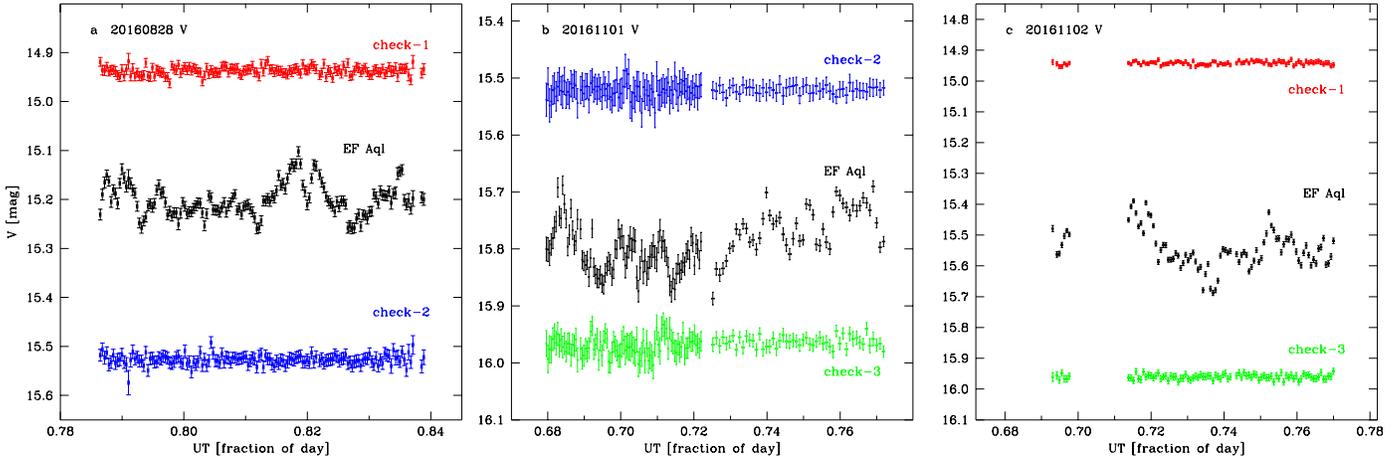
Here we report optical CCD photometry of EF Aql and detection of flickering in Johnson V and B bands.

## 2 Observations

During the period August - November 2016, we secured CCD photometric monitoring with 5 telescopes equipped with CCD cameras:

- the 2.0 m RCC telescope of the National Astronomical Observatory Rozhen, Bulgaria (CCD VersArray 1300 B,  $1340 \times 1300$  px);

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**Fig. 1** Detection of optical flickering of 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.

**Table 1** CCD observations of EF Aql. In the table are given as follows: 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, typical observational error.

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

**Table 2** V band observations of EF Aql and the check stars in the field. The average magnitude and  $\sigma_{rms}$  are given for each object.

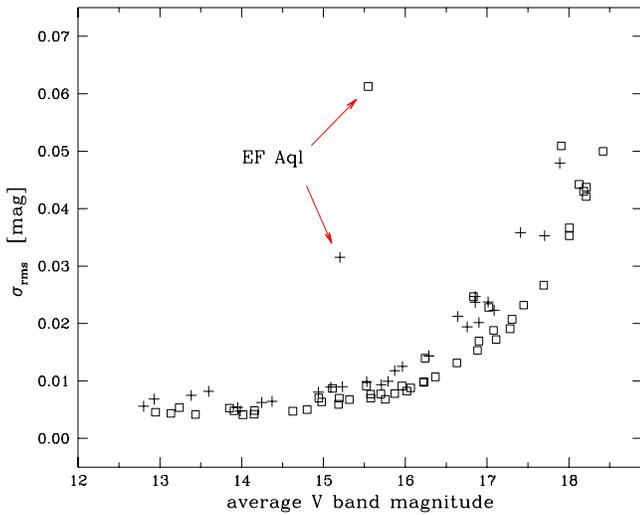
date	telescope	filter	EF Aql mean $\pm \sigma_{rms}$	check-1 mean $\pm \sigma_{rms}$	check-2 mean $\pm \sigma_{rms}$	check-3 mean $\pm \sigma_{rms}$
20160828	2.0 m	V	15.201 $\pm$ 0.033	14.937 $\pm$ 0.008	15.527 $\pm$ 0.010	15.964 $\pm$ 0.013
20161028	60 cm Bel	V	15.773 $\pm$ 0.104	14.986 $\pm$ 0.038	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

- the 50/70 cm Schmidt telescope of NAO Rozhen (SBIG STL11000M CCD, 4008  $\times$  2672 px);
- the 60 cm telescope of the Belogradchick Astronomical Observatory (SBIG ST8 CCD, 1530  $\times$  1020 px);
- the 30 cm astrograph of IRIDA observatory (CCD camera ATIK 4000M, 2048  $\times$  2048 px);
- the automated 41 cm telescope of the University of Jaén, Spain - ST10-XME CCD camera with 2184  $\times$  1472 px (Martí, Luque-Escamilla, & García-Hernández 2017).

All the CCD images have been bias subtracted, flat fielded, and standard aperture photometry has been performed. The

data reduction and aperture photometry are done with IRAF and have been checked with alternative software packages. A few objects from the APASS catalogue (Munari et al. 2014; Henden et al. 2016) have been used as comparison stars. As check stars we used USNO U0825.17150321, USNO U0825.17161750 and USNO U0825.17157668. In Fig. 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 on Fig. 1. For each run we measure the minimum, maximum, and average brightness in the corre-



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

sponding band, plus the standard deviation of the run. For each run we calculate the root mean square (rms) deviation

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

where  $\bar{m}$  is the average magnitude in the run.  $\sigma_{rms}$  calculated in this way includes the contributions from the variability of the star (if it exists) and from the measurement errors. For non-variable 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 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 (Warner 1995, Bruch 2000), is evident on all our observations in B and V bands. It is not detectable in I band, suggesting that the I flux is dominated by the red component. Fig. 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  $\sigma_{rms}$  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 2 we give the mean magnitude and  $\sigma_{rms}$  of EF Aql and the three check stars. The root mean square deviation  $\sigma_{rms}$  of EF Aql exceeded the rms deviation expected from the check star by more than a factor of 2.

In Fig. 2 we plot  $\sigma_{rms}$  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 root mean square deviation is  $\sigma_{rms}(EFAql) = 0.033$  mag. For stars with similar brightness we have  $\sigma_{rms} \approx 0.009$  mag. In other words,  $\sigma_{rms}$  of EF Aql is more than three times larger than expected from observational errors. During run 20161102, EF Aql exhibits flickering with higher amplitude of about 0.30 mag. The root mean square variability is  $\sigma_{rms}(EFAql) = 0.061$  mag. For stars with similar brightness we have  $\sigma_{rms} \approx 0.008$  mag. In other words, the rms of EF Aql is more than seven times larger than that expected from observational errors.

Using our simultaneous B and V band observations obtained on 28 August 2016 (see Table 1) and interstellar extinction  $A_V = 0.45$  (Margon et al. 2016), we calculate the dereddened colour of the flickering source as  $(B - V)_0 = 0.35 \pm 0.05$ . For comparison, the average  $(B - V)_0$  colour of the flickering source is  $0.25 \pm 0.21$  in the recurrent novae T CrB and RS Oph, and  $0.10 \pm 0.20$  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 28 August 2016 and 4 September 2016, respectively. Applying  $A_V = 0.45$  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 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 non-variable light from the red giant, contributes about 20% of the flux at V band. Fig. 1 demonstrates that the V band flux can change by more than 5% (0.05 mag) in less than 5 minutes and more than 20% (0.20 mag) in less than one hour. Taking into account the contribution of the red giant, these rapid fluctuations correspond to variations up to  $\pm 25\%$  (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 Sokolowski & Bildsten (2010).

The flickering (stochastic photometric variations on timescales of a few minutes with amplitude of a few  $\times 0.1$  magnitudes) is a variability typical for the accreting white dwarfs 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 white dwarf, 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 white dwarf.

A comparison of the flickering of EF Aql with the flickering 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 I, but well visible in B and V bands. In RS Oph the mass accretion rate is of about  $\sim 2 \times 10^{-8} M_{\odot} \text{ yr}^{-1}$  (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 V band. Overall, the relative colour dependence of flickering in EF Aql implies that the mass accretion rate is lower than that in RS Oph, but not too much lower, probably of a few  $\times 10^{-9} M_{\odot} \text{ yr}^{-1}$ . Le Bertre et al. (2003) estimated that the mass donor in EF Aql is losing mass at a rate  $3.8 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$ . We used 2MASS  $K=5.36$  mag and IRAS 12-micron flux (4.78 Jy) to estimate the color  $K-[12]$  defined by Gromadzki et al. (2009). Then, applying their Eq. 4, we determined a mass loss rate of  $2 \times 10^{-6} M_{\odot} \text{ yr}^{-1}$  for EF Aql. This means that the white dwarf 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 near UV band (NUV, 1771 Å– 2831 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 all the counts are inside the aperture and no contaminating sources are within the background subtraction annulus. We thus obtain the following fluxes:

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

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 variable mass accretion rate onto the white dwarf.

There are more than 200 symbiotic stars known (Belczyński et al. 2000). Among them flickering is detected in only 11 objects (including EF Aql), i.e. in 5% of the cases (see Sect. 1 for references). On the basis of their infrared properties, the symbiotic stars are divided in three main groups S-, D-, and D'-type (Allen 1982; Mikołajewska 2003). There are about 30 symbiotic stars classified as symbiotic Miras (Whitelock 2003). In three of them flickering is present, i.e. 10% of the objects. It seems that flickering more often can be detected in symbiotic Miras than among S- and D'-type symbiotics. Bearing in mind this, 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 (Taylor et al. 1986; Crocker et al. 2002; Brocksopp et al. 2004), although not as powerful as in X-ray binaries and microquasars. Nevertheless, some of their collimated ejecta display a combination of thermal and non-thermal 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  $3\sigma$  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 that 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 be thus desirable. With the similarities between RS Oph and EF Aql noted above, it may be worthwhile to look 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 hours photometric observations of the symbiotic Mira EF Aql. We find that EF Aql exhibits short-term optical variability (flickering) on a time scale of minutes. The detected amplitude is about 0.15 - 0.30 mag in B and V bands. The root mean square deviation of EF Aql is from three to seven times larger than that expected from observational errors. The presence of flickering strongly suggests that the hot component is a white dwarf. It seems that the flickering is more often seen in symbiotic Miras than in the general population of symbiotic stars.

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