The cataclysmic variable AE Aquarii: B-V colour of the flares

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We report simultaneous observations of the flaring behaviour of the cataclysmic variable star AE Aqr. The observations are in Johnson B and V bands. The colour-magnitude diagrams (B-V versus V and B-V vs. B) show that the star becomes bluer as it becomes brighter. In our model AE Aqr behaviour can be explained with flares (fireballs) with 0.03 \( \leq B - V \leq 0.30 \) and temperature in the interval 8000 \( \leq T \leq 12000 \).

1 Introduction

AE Aqr is a bright \( (V \sim 11 \text{ mag}) \) unusual cataclysmic variable, displaying strong flaring activity (e.g. Chincarini & Walker 1974). Its binary nature was discovered by Joy (1954). In the system a spotted K type dwarf \( (\text{K0-K4 IV} \& \text{Walker} 1974) \). Its binary nature was discovered by Joy in the recent past \( (\text{Casares et al. 1996}) \). The observations of the short term variability of AE Aqr are obtained with 4 telescopes: the 2.0 m RCC telescope, the 50/70 cm Schmidt telescope, the 60 cm telescope of the Bulgarian National Astronomical Observatory Rozhen, and the 60 cm telescope of the Belogradchick Astronomical Observatory. All of the telescopes are equipped with CCD cameras. All the CCD images have been bias subtracted, flat fielded, and standard aperture photometry has been performed. The data reduction and aperture photometry were done with \textsc{iraf} and checked with alternative software packages. The typical accuracy of the photometry was 0.005–0.010 mag. Journal of observations is given in Table 1. The first four dates are partly analyzed in Zamanov et al. (2012).

The observations demonstrate that the plasma cannot be a product of mass accretion onto the white dwarf (Itoh et al. 2006). Non-detection of very high energy (TeV) \( \gamma \)-rays in MAGIC observations (Aleksić et al. 2014) probably points that the white dwarf is not acting as ejector and from our point of view the propeller model is the better one.

In the optical bands AE Aqr exhibits atypical flickering consisting of large optical flares with amplitude \( \leq 1 \) magnitude in Johnson V band. The flares are visible about one third of the time and have typical rise time 200 – 400 s (van Paradijs, van Amerongen & Kraakman, 1989; Zamanov et al. 2012). The flares are also visible in the X-rays (Mauche et al. 2012) and in submillimeter wavelengths (Torkelsson 2013).

Here we explore the behaviour of AE Aqr in optical B and V bands, construct the colour-magnitude diagram, and estimate the B-V colour of the flares and temperature of the fireballs.

2 Observations

The observations of the short term variability of AE Aqr are obtained with 4 telescopes: the 2.0 m RCC telescope, the 50/70 cm Schmidt telescope, the 60 cm telescope of the Bulgarian National Astronomical Observatory Rozhen, and the 60 cm telescope of the Belogradchick Astronomical Observatory. All of the telescopes are equipped with CCD cameras. All the CCD images have been bias subtracted, flat fielded, and standard aperture photometry has been performed. The data reduction and aperture photometry were done with \textsc{iraf} and checked with alternative software packages. The typical accuracy of the photometry was 0.005–0.010 mag. Journal of observations is given in Table 1. The first four dates are partly analyzed in Zamanov et al. (2012).
3 Light curves in B and V bands

The stochastic light variations on timescales of a few minutes (flickering) with amplitude of a few×0.1 magnitudes is a type of variability observed in the three main classes of binaries that contain white dwarfs accreting material from a companion mass-donor star: cataclysmic variables (CVs), supersoft X-ray binaries, and symbiotic stars (e.g. Sokoloski 2003). Stochastic light variations are not only observed in accreting white dwarfs, but also in accreting black holes and neutron stars (e.g. Belloni & Stella 2014; Scaringi 2015).

The flickering of AE Aqr is first detected by Henize (1949). Five-colour optical photometry in Walraven system made in 1984 and 1985 was analyzed by van Paradijs et al. (1989). In Fig. 1 is plotted the variability of AE Aqr in B and V bands.
and V bands. The calculated colour index is also plotted. All data are drawn on identical scale, in this way 0.1 magnitude has the same size on all Y axes.

Histograms representing the distribution of B and V band magnitudes and B – V colour are plotted in Fig. 2. B magnitude is measured for $N_{pts} = 2733$. The values are in the interval $10.767 \leq B \leq 12.565$, with average value $\overline{B} = 12.006$, standard deviation of the mean $\sigma_B = 0.320$ and median value $< B >= 12.112$. V magnitude is measured for $N_{pts} = 4564$. The values are the interval $10.355 \leq V \leq 11.563$, with average value $\overline{V} = 11.235$, $\sigma_V = 0.199$ and median value $< V >= 11.288$. The histograms of B and V band magnitudes have a well defined peak and extended tail to the higher brightness. The peaks of the distributions are at $V = 11.35 \pm 0.03$ and at $B = 12.22 \pm 0.03$ for the V and B band respectively. B – V is measured for $N_{pts} = 2327$ data points. The values are the interval $0.354 \leq B – V \leq 1.037$, with average value $\overline{B} – \overline{V} = 0.794$, $\sigma_{B-V} = 0.126$ and median value $< B – V >= 0.829$.

The histogram of B – V colour have a well defined peak at $B – V = 0.88 \pm 0.03$ and extended tail to the blue colour. The tails in all three histograms plotted in Fig. 2 are due to the appearance of the flares in the light curve.

### 4 Colour-magnitude diagram

In Fig. 2 are shown the relation between the brightness of the star in B and V band and its B – V colour. It is visible that the star becomes bluer when it brightens and redder when it fades, indicating that the flares change the colour of the system.

Pearson, Horne & Skidmore (2003) have supposed that the flares of AE Aqr are due to the ejection and expansion of isothermal fireballs. Using their improved model (Pearson, Horne & Skidmore 2005), Zamanov et al. (2012) have estimated the fireballs temperatures of 10000-25000 K, masses of $(7 – 90) \times 10^{19}$ g, and sizes of $(3 – 7) \times 10^6$ cm (using a distance of d=86 pc). These values refer to the peak of the flares observed in the UBVRI bands. Here we use E(B-V)=0 (La Dous 1991), and construct colour-magnitude diagrams. These diagrams should contain information about the temperature of the flares. We model the behaviour of AE Aqr in the following way:

- The peak of the V band histogram corresponds to $V=11.35$. The peak of the B band histogram corresponds to $B=12.22$. We adopt these values as basic level.
- To this level we add an additional source (fireball) with constant $B – V$. We vary the brightness of this additional source from 15.0 mag to 10.95 magnitude in V.
- Because the stellar magnitude scale is logarithmic, during the calculations we convert the magnitudes into fluxes using Bessell (1979) calibration of a zero magnitude star. After it we reconvert the fluxes into magnitudes.
- We repeat this procedure with different $B – V$ colour of the fireball. We achieved the best agreement with $B – V=0.19$ of the fireball.

The basic level is

$$F_{B0} = 6.601 \times 10^{-9} \times 10^{-12.22/2.5} \text{ erg cm}^{-2} \text{s}^{-1} \text{ Å}^{-1},$$

$$F_{V0} = 3.610 \times 10^{-9} \times 10^{-11.35/2.5} \text{ erg cm}^{-2} \text{s}^{-1} \text{ Å}^{-1},$$

where $F_{V0}$ and $F_{B0}$ are the fluxes corresponding to the peak of the histograms in V and B band respectively. The emission of the fireball is:

$$F_{Vf} = 3.610 \times 10^{-9} \times 10^{-m_{Vf}/2.5} \text{ erg cm}^{-2} \text{s}^{-1} \text{ Å}^{-1},$$

$$F_{Bf} = 6.601 \times 10^{-9} \times 10^{-m_{Bf}+c_f}/2.5 \text{ erg cm}^{-2} \text{s}^{-1} \text{ Å}^{-1},$$

where $m_f$ is the V band magnitude of the fireball, $c_f$ is its B-V colour. $F_{Vf}$ and $F_{Bf}$ are the fluxes of the ball emitted in V and B band respectively. The brightness of the system ($F_V$ and $F_B$) is the sum of the fluxes of the basic level and the fireball:

$$F_V = F_{V0} + F_{Vf},$$

$$F_B = F_{B0} + F_{Bf},$$

$$m_V = -2.5 \log(F_V/(3.610 \times 10^{-9})),$$

$$m_B = -2.5 \log(F_B/(6.601 \times 10^{-9})).$$

where $m_V$ and $m_B$ are the brightness of the system in magnitudes for V and B band respectively. In Fig. 3 we plot with green, red and blue colour three lines corresponding to B-V colour of the fireball $c_f = 0.03$, 0.19 and 0.30. These B-V colours correspond to black body temperatures 12000 K, 9400 K and 8000 K, respectively. The model with $c_f = 0.19$ produces good agreement with the observations in the three panels: V versus B – V (Fig. 3d), B versus B-V (Fig. 3c) and B versus V (Fig. 3b). On Fig. 3a and Fig. 3b with red crosses are marked four positions corresponding to V brightness of the fireball $m_f = 11.0, 11.5, 12.0, 14.0$.

The largest flares of AE Aqr correspond to an additional source with $V \approx 10.95$ mag, which is the brightness of the most luminous flares (fireballs) in our data set. Comparing this value with the peak of the histogram we derive that in V band the strongest flares emit 1.4 times as much energy as the non-flaring components of AE Aqr (in the B band they emit 2.2 times). The values are similar but higher than the value 1.5 times for the strongest flares observed in B band in 1983 (Bruch 1991).

### 5 Discussion

AE Aqr is a highly variable object exhibiting flaring behaviour in the optical (Chincarini & Walker 1981), radio (Bastian et al. 1988), ultraviolet (Eracleous & Horne 1996), and X-rays (Choi & Dotani 2006). Five-colour (Walraven system) observations of the cataclysmic variable AE Aqr were made in 1984 and 1985 (van Paradijs et al. 1989). The optical flux emitted in the flares is about 3 times the quiescent accretion flux. It seems to be a slight phase dependence of the activity – while flares can definitely occur...
at any phase, the probability for very strong variations is higher in the first half of the orbital cycle than in the second half (Bruch & Grutter 1997).

Different mechanisms are discussed to explain the flares of AE Aqr:

1. the flares are due to an accretion instability that occurs within a few white-dwarf radii, perhaps as a result of magnetospheric gating of the inflowing matter at the inner edge of the accretion disc (van Paradijs et al. 1989).

2. blobs (fireballs) launched from the magnetosphere (Wynn et al. 1997; Pearson, Horne & Skidmore 2002).

In the context of the fragmented accretion flow/magnetic propeller scenario we assume that the flares represent the excitation of gaseous blobs upon encounter with the propeller, and their subsequent radiative cooling as they are expelled from the system. The gas stream emerging from L1 encounters a rapidly spinning magnetosphere of the white dwarf. The rapid spin causes the stream material to be dragged toward co-rotation with the magnetosphere. As it occurs outside the corotation radius the magnetosphere accelerates velocity of the material beyond the escape velocity (Wynn et al. 1997).

The colour-magnitude diagrams (Fig. 3) indicate that the balls have temperatures in the interval $8000 \leq T_f \leq 12000$ K and V band magnitude $14.0 \leq m_f \leq 11.0$. Our result point to that all the fireballs have similar temperature $\approx 9400$ K. Taking into account the observational errors and errors in the fit, we estimate the average temperature of the fireballs $9400 \pm 600$ K. There is no tendency (at least in our data) for the brighter flares to have higher or lower temperature. This is in agreement with the suppositions that the flares are isothermal (Pearson et al. 2003). This temperature is similar to that of the flickering source of the recurrent nova RS Oph $T = 9500 \pm 500$ K (Zamanov et al. 2010).

6 Conclusion

We performed 37.5 hours simultaneous observations in Johnson B and V bands of the cataclysmic variable AE Aqr. On the basis of these observations the $B - V$ colour is calculated for 2327 observational points. The colour-magnitude diagrams show that the star becomes bluer as it becomes brighter. We modeled the brightness (B and V band) and $B-V$ colour changes, supposing additional source of energy (blobs). The model indicates that the blobs (flares) have on average $B - V \approx 0.19$, which corresponds to an average temperature of the fireballs $\approx 9400 \pm 600$ K.

A related question is whether the colour-magnitudes diagrams and model discussed here are relevant to other cataclysmic and symbiotic stars with flickering.

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Fig. 3  Colour-magnitude diagrams of the peculiar cataclysmic variable AE Aqr - left panels: a) V versus $B - V$, b) B versus $B - V$, c) B versus V. On the right panels the models are over-plotted.

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