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UBVRIu′ OBSERVATIONS OF THE FLICKERING OF THE JET EJECTING SYMBIOTIC STAR MWC 560

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Abstract. We report observations of the flickering variability of the symbiotic star MWC 560 on the basis of simultaneous observations in $UBVRI$ bands. We find that MWC 560 has a flickering source with $(U-B)_0 = -0.93 \pm 0.05$, $(B-V)_0 = 0.01 \pm 0.06$, $(V-R)_0 = 0.43 \pm 0.08$, a source temperature $T_{\rm fl} = 11780 \pm 300$ K and luminosity $L_{\rm fl} \approx 20\ L_\odot$ on 2009 November 14 (using a distance of $d = 2.5$ kpc and $E_{B-V} = 0.15$). On 2010 January 11, we find $(U-B)_0 = -0.61 \pm 0.05$, $(B-V)_0 = -0.01 \pm 0.05$, $(V-R)_0 = 0.46 \pm 0.02$, $T_{\rm fl} \approx 9100 \pm 300$ K, $L_{\rm fl} \approx 38\ L_\odot$.

1. INTRODUCTION

Discovered by Merrill & Burwell (1943) as an object with bright hydrogen lines, MWC 560 (V694 Mon) is a symbiotic binary system, which consists of a red giant and a white dwarf. Gromadzki et al. (2007), using optical and near-IR light curves, refined it as $P_{\rm orb} = 1931 \pm 162$ day. The white dwarf mass is ~ 0.9 (Zamanov, Gomboc & Latev, 2011). and the orbit is highly eccentric, with $e \sim 0.7$ (Zamanov et al. 2010).

The most spectacular features of this object are the collimated ejections of matter with velocities of up to ~ 6000 km s^{-1} (Tomov et al. 1992; Stute & Sahai 2009) and the resemblance of its emission line spectrum to that of the low-redshift quasars (Zamanov & Marziani 2002).

The flickering (stochastic light variations on timescales of a few minutes with amplitude of a few×0.1 magnitudes) is a variability observed in the three main types of binaries that contain white dwarfs accreting material from a companion mass-donor star: cataclysmic variables (CVs), supersoft X-ray binaries, and symbiotic stars (Sokoloski 2003). The systematic searches for flickering variability in symbiotic stars and related objects (Dobrzycka et al. 1996; Sokoloski, Bildsten & Ho 2001; Gromadzki et al. 2006) have shown that among ~ 200 symbiotic stars known, to-

date flickering has only been detected in 9 objects. The flickering of MWC 560 was detected by Tomov et al. (1990) and Michalitsianos et al. (1993).

To improve our understanding of this object, our aims are: (1) to perform $UBVRIu'$ observations of the flickering, and (2) to throw light on the origin of the flickering.

2. OBSERVATIONS

On 2004 December, as exploratory observations that led to the full programme, we obtained two runs with the RATCam CCD camera (2048x2048 pixel, field of view 4.6 arcmin) on the 2-m Liverpool Telescope (Steele et al. 2004) in the Sloan u' band. The amplitude of the flickering in u' was 0.34 and 0.49 mag for the first and second runs respectively (see Table 1).

On the night of 2009 November 14, we observed MWC 560 simultaneously with four telescopes equipped with CCD cameras. The 2m RCC telescope of the National Astronomical Observatory Rozhen observed in the U band, equipped with a CCD VersArray 1300 B (1340x1300 px, field of view 6'x6'). The 50/70 cm Schmidt telescope observed in the B band (CCD FLI PL 16803, 4096x4096 px, used 1024x1024 px, 19' x 19'). The 60 cm Rozhen telescope observed in the R band (FLI PL 9000 CCD with 3056 x 3056 pixels and 18'x18'); the 60 cm telescope of the Belogradchick Astronomical Observatory in the V band (FLI PL 9000 CCD, 3056 x 3056 px, 18'x18').

On the night of 2010 January 11, we observed MWC 560 simultaneously with three telescopes of NAO Rozhen. The 2m RCC telescope of the National Astronomical Observatory Rozhen equipped with a dual channel focal reducer observed in U and V bands. In the U band a Photometrics CCD (1024x1024 px, field of view 7.6'x7.6') has been used, and in the V band a VersArray CCD (512x512 px, 7.6'x7.6'). The 50/70 cm Schmidt telescope observed in the B band. The 60 cm Rozhen telescope observed in the R and I bands.

On the night of 2010 March 15, we observed MWC 560 with the 60 cm Rozhen telescope repeating V and I bands.

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. The comparison stars of Henden and Munari (2006) have been used.

The results of our observations are summarized in Table 1 and plotted in Fig. 1. For each run we measure the minimum, maximum, and average brightness in the corresponding band, plus the standard deviation of the run.

3. FLICKERING LIGHT SOURCE

As can be seen in Fig. 1 and Table 1, during our observations MWC 560 exhibited variability on a time scale of 1-30 minutes with amplitude $0.1 - 0.3$ mag in V. The amplitude increases to shorter wavelengths and decreases to longer. In the I band this variability is almost undetectable.

The distance to MWC 560 is estimated $d = 2.5 \pm 0.3$ kpc (Meier et al. 1996). Schmid et al. (2001) give $d = 2.5 \pm 0.7$ kpc and $E_{B-V} = 0.15 \pm 0.05$ mag. We assume $d = 2.5$ kpc, $E_{B-V} = 0.15$ mag, and an extinction law as given in Zombeck (1990). This gives the interstellar absorption to MWC 560: $A_U = 0.754$ mag, $A_B =$

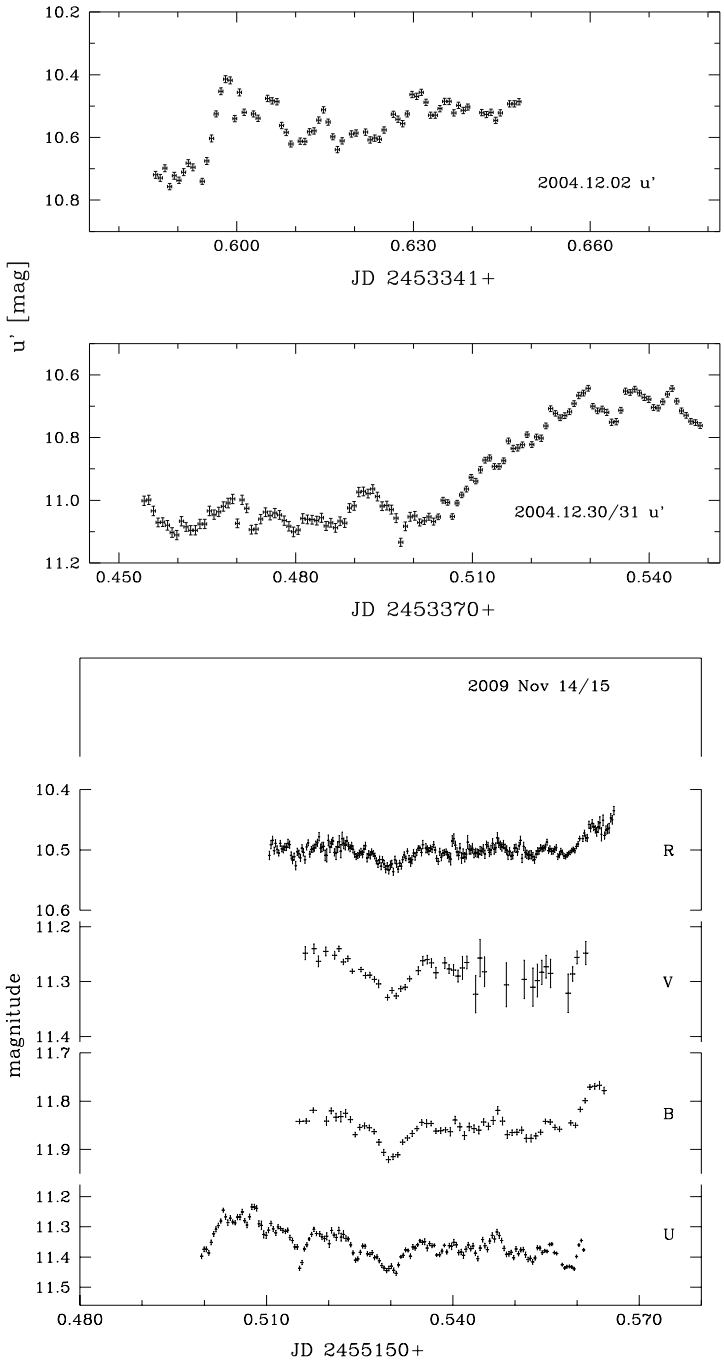

Figure 1: Variability of MWC 560: in the SDSS u' band on 2004 December 02; in the SDSS u' band on 2004 December 30/31; in the $UBVR$ bands on 2009 November 14/15;

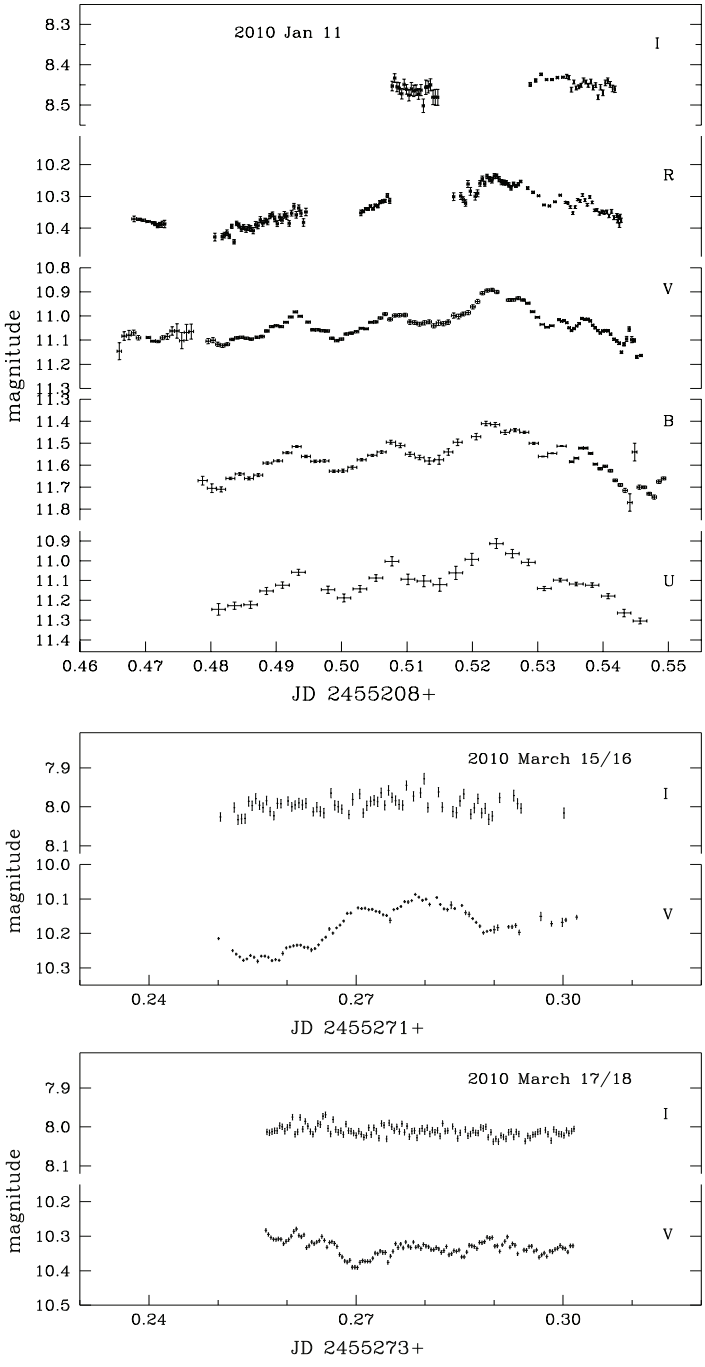

Figure 2: Variability of MWC 560: in the $UBVRI$ bands on 2010 January 11/12; in the VI bands on 2010 March 15/16; in the VI bands on 2010 March 17/18.

Table 1: CCD observations of MWC 560. In the table are given as follows: the telescope, band, UT-start and UT-end of the run, exposure time and number of CCD images obtained.

date telescope	band	UT start-end	Exp-time [sec]	N_{pts}
2004 Dec 02		JD 2453341		
2.0m LT	SDSS u'	02:04 - 03:33	60	69
2004 Dec 30/31		JD 2453370		
2.0m LT	SDSS u'	22:54 - 01:10	60	120
2009 Nov 14/15		JD 2455150		
2m RCC	U	23:59 - 01:28	30	159
50/70 cm Schmidt	B	00:21 - 01:33	60	60
60 cm Belogr	V	00:23 - 01:28	60	45
[a] part	V	00:23 - 00:59	60	29
60 cm Rozhen	R	00:14 - 01:35	20	221
2010 Jan 11/12		JD 2455208		
2m RCC	U	23:31 - 01:07	180	26
50/70 cm Schmidt	B	23:28 - 01:11	120,60	58
2m RCC	V	23:11 - 01:06	60,30	117
60 cm Rozhen	R	22:34 - 01:02	10,30	120
60 cm Rozhen	I	00:11 - 01:00	30,10	48
2010 March 15		JD 2455271		
60 cm Rozhen	V	18:00 - 19:16	30	82
60 cm Rozhen	I	18:00 - 19:17	3	67
2010 March 17		JD 2455273		
60 cm Rozhen	V	18:10 - 19:14	15	120
60 cm Rozhen	I	18:10 - 19:14	5	117

[a] only the first (better) part of the V band observations with the 60 cm Belogr. telescope

Table 2: CCD observations of MWC 560. In the table are given as follows: the telescope, band, average magnitude in the corresponding band, minimum – maximum magnitudes in each band, standard deviation of the mean, the range of observational error.

date telescope	band	average [mag]	min-max [mag]-[mag]	stdev [mag]	err [mag]
2004 Dec 02		JD 2453341			
2.0m LT	SDSS u'	10.562	10.414 - 10.757	0.084	0.010-0.011
2004 Dec 30/31		JD 2453370			
2.0m LT	SDSS u'	10.924	10.643 - 11.134	0.159	0.009-0.015
2009 Nov 14/15		JD 2455150			
2m RCC	U	11.358	11.234 - 11.454	0.048	0.005-0.014
50/70 cm Schmidt	B	11.850	11.767 - 11.921	0.031	0.005-0.011
60 cm Belogr	V	11.281	11.240 - 11.329	0.024	0.004-0.040
[a] part	V	11.279	11.240 - 11.329	0.025	0.004-0.012
60 cm Rozhen	R	10.499	10.435 - 10.536	0.016	0.004-0.011
2010 Jan 11/12		JD 2455208			
2m RCC	U	11.118	10.913 - 11.304	0.094	0.009-0.033
50/70 cm Schmidt	B	11.586	11.410 - 11.770	0.085	0.002-0.040
2m RCC	V	11.045	10.892 - 11.169	0.056	0.002-0.035
60 cm Rozhen	R	10.338	10.236 - 10.443	0.051	0.002-0.012
60 cm Rozhen	I	8.454	8.424 - 8.502	0.016	0.002-0.020
2010 March 15		JD 2455271			
60 cm Rozhen	V	10.183	10.087 - 10.281	0.058	0.003-0.012
60 cm Rozhen	I	7.995	7.928 - 8.033	0.021	0.011-0.015
2010 March 17		JD 2455273			
60 cm Rozhen	V	10.334	10.279 - 10.391	0.023	0.005-0.006
60 cm Rozhen	I	8.011	7.969 - 8.038	0.013	0.007-0.007

[a] only the first (better) part of the V band observations with the 60 cm Belogr. telescope

Table 3: Magnitudes and colours of the flickering light source of MWC 560 (only the colours are corrected for interstellar extinction).

	14.11.2009	11.01.2010	29.12.2010
U	14.04 ± 0.05	13.12 ± 0.04	12.08 ± 0.07
B	14.85 ± 0.06	13.60 ± 0.02	13.11 ± 0.07
V	14.69 ± 0.06	13.46 ± 0.02	12.75 ± 0.06
R	14.19 ± 0.07	12.93 ± 0.02	12.94 ± 0.09
$(U-B)_0$	-0.93 ± 0.05	-0.61 ± 0.05	-1.16 ± 0.08
$(B-V)_0$	0.01 ± 0.06	-0.01 ± 0.02	0.21 ± 0.09
$(V-R)_0$	0.43 ± 0.08	0.46 ± 0.02	-0.26 ± 0.10
$L_{\rm fl}$ $[L_\odot]$	20 ± 2	38 ± 3	88 ± 8
$T_{\rm fl}$ [K]	11800 ± 300	9100 ± 300	13550 ± 500
$R_{\rm fl}$ $[R_\odot]$	1.1 ± 0.1	2.7 ± 0.2	1.68 ± 0.16

0.628 mag, $A_V = 0.477$ mag, $A_R = 0.400$ mag, $A_I = 0.304$ mag. If we use the extinction law as given in Cardelli et al. (1989) than we have $A_U = 0.729$ mag, $A_B = 0.616$ mag, $A_V = 0.464$ mag, $A_R = 0.392$ mag, $A_I = 0.285$ mag, and the results will be practically the same.

3. 1. COLOURS OF THE FLICKERING SOURCE

Bruch (1992) proposed that the light curve of CVs can be separated into two parts – constant light and variable (flickering) source. We assume that all the variability in each night is due to flickering. In these suppositions the flickering light source is considered 100% modulated. Following these assumptions, we calculate the flux of the flickering light source as $F_{\rm fl} = F_{\rm av} - F_{\rm min}$, where $F_{\rm av}$ is the average flux during the run and $F_{\rm min}$ is the minimum flux during the run (corrected for the typical error of the observations). $F_{\rm fl}$ has been calculated for each band, using the values given in Table 1 and Bessel (1979) calibration for the fluxes of a zero magnitude star.

The calculated magnitudes and colours of the flickering light source are given in Table 3. Adopting these results, we find that the flickering light source contributes about 3% of the light in the R band, 4% in V, 6% in B, and 8% in U (Nov 2009); 9% of the light in the R band, 11% in V, 16% in B, and 16% in U (Jan 2010).

Zamanov et al. (2011) reported simultaneous observations in 5 bands of MWC 560 on 2010 December 29/30 during the recent active phase. For completeness all the results are given in Table 3.

3. 2. TEMPERATURE AND SIZE OF THE FLICKERING SOURCE

The derived $(U-B)_0$ colour corresponds to a B1-B5V star ($T_{\rm eff} \approx 24000 - 16000$ K) and a black body with $T \approx 8000 - 12000$ K. The $(B-V)_0$ colour corresponds to an

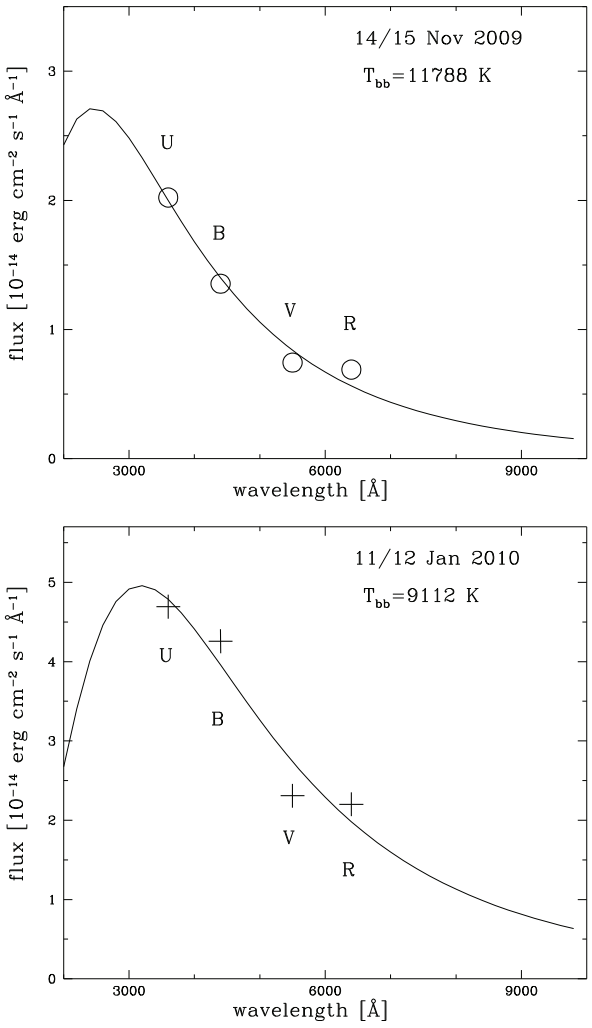

Figure 3: Dereddened fluxes of the flickering light source of MWC 560. The solid line represents a black body fit.
(upper panel): 2009 Nov 14/15 (circles). The fit is $T_{bb} = 11788$ K, radius $R = 1.07$ R$_\odot$, located at distance $d = 2.5$ kpc.
(down panel): 2010 Jan 11/12 (pluses), $T_{bb} = 9112$ K, radius $R = 2.74$ R$_\odot$.

B8-A8V ($T_{\rm eff} \approx 8000 - 13000$ K) star and a black body with $T \approx 8000 - 15000$ K. These estimates give an approximate temperature of the flickering light source $T_{\rm fl} = 8000 - 15000$ K (we note that $(V - R)_0$ gives a lower resulting temperature ($T_{\rm eff} = 5000 - 5500$ K) but the R band is dominated by the contribution of the red giant).

In Fig. 3 we plot these magnitudes transformed to fluxes. Adopting $d = 2.5$ kpc and using a black body fit ($nfit1d$ routine of IRAF), we calculate for the flickering light source: $T_{\rm fl} = 11788 \pm 300$ K, $R_{\rm fl} = 1.1$ R$_\odot$, $L_{\rm fl} = 20$ L$_\odot$ (2009 Nov 14) and $T_{\rm fl} = 9112 \pm 300$ K, $R_{\rm fl} = 2.45$ R$_\odot$, $L_{\rm fl} = 38$ L$_\odot$ (2010 Jan 11). Using all data normalized to V band we calculate $T_{\rm fl} \approx 10100 \pm 300$ K.

3. 3. QUASIPERIODS

In our Jan 2010 observations a quasiperiod of 21.8 ± 1.2 min is visible. From the run on 2004 December 2, a quasiperiod of 11.8 ± 1.1 min is visible. From the run on 2010 December 29, a quasiperiod of 51 ± 2 min is detectable.

Quasi-periods observed in the light curves of MWC 560 range from 11 to 167 min (Tomov et al. 1996). These quasi periods correspond to Keplerian periods of gas in an accretion disk at distances $0.15 - 1.0$ R$_\odot$, around a 0.9 M$_\odot$ white dwarf.

3. 4. ACTIVE PHASE

Our observations are obtained before and during the recent outburst, which reached the peak brightness in the end of December 2010 (Goranskij et al. 2011). The calculated parameters (Table 3) show that the flickering light source becomes hotter and more luminous, but does not change its size, during the recent outburst.

4. CONCLUSIONS

We report our CCD observations of the flickering variability of the jet-ejecting symbiotic star MWC 560, with 5 telescopes in the $UBVRIu'$ bands. MWC 560 has a flickering source with $(U-B)_0 = -0.93$, $(B-V)_0 = +0.01$, $(V-R)_0 = +0.43$ (14 Nov 2009), and $(U-B)_0 = -0.61$, $(B-V)_0 = -0.01$, $(V-R)_0 = +0.46$ (11 Jan 2010).

For the flickering light source in MWC 560 we estimate $T_{\rm eff} \approx 9100 - 11800$ K, which is similar to the temperature of the bright spot in CVs. Using a distance of $d = 2.5$ kpc, we find size $R_{\rm fl} \approx 1 - 2.5$ R$_\odot$, and luminosity $L_{\rm fl} \sim 20 - 40$ L$_\odot$. These values refer to November 2009 - January 2010.

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