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Photometric observations of Epsilon Aurigae during the eclipse of 2009–2011

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Epsilon Aurigae is a bright binary system, in which an F0 supergiant is eclipsed by a dark disk around the companion, every 27.1 years. Although the star has been observed and studied for nearly two centuries, it remains an usolved mystery. For the latest ε Aur eclipse, which occurred in 2009-2011, an international observing campaign was organized. In this publication, multicolor BVR photometric observations obtained in the framework of this campaign, are presented. Part of these data have been corrected for atmospheric extinction and transformed to the standard Johnson's photometric system.

Key words: binaries: eclipsing, stars: individual: Eps Aur

INTRODUCTION

The first observations of ε Aur were made at the beginning of the 19th century. Nevertheless, the nature of this star system is still not well-understood. Following the seven instances of eclipse observations before 1984, it became almost certain, that the object causing eclipses was a massive, dark dusty disc surrounding a secondary object. The properties of the stellar components, as well as the evolutionary status of the system, remained unknown. There was no proof indicating which of the two most promising models – the high mass or the low mass model (both described by Guinan & DeWarf [3]) – was correct. The opportunity to determine this presented itself with 2009-11 eclipse. Keeping in mind that an eclipse occurs only once every 27 years, in order to use this opportunity to the fullest, an international campaign was organized [4].

We contributed to the campaign with photometric and spectroscopic observations, and our preliminary results were published by Tomov et al. [5]. Our photometric data, however, were not then fully calibrated due to lack measurements of photometric standards. In this paper, we report on the correction for atmospheric extinction and on transformation to the standard Johnson's system, which was performed for part of our photometric data.

OBSERVATIONS AND DATA REDUCTION

Our collective data include multicolor BVR photometry data obtained in 2009-2011. Observations were carried out with three different photometric systems at two observatories. Two instruments were located at the Torun Centre for Astronomy of Nicolaus Copernicus University, and a third was located at the Olsztyn Planetarium and Astronomical Observatory. One of the telescopes in Torun was a 60-cm Cassegrain telescope with a CCD STL-1001E camera (TCfA C60). The second one was an achromatic telephoto lens MC APO Telezenitar-M 135/2.8 with a SBIG ST-8XE CCD camera (TCfA SC). In Olsztyn, a 25/250-cm Schmidt-Cassegrain with a SBIG ST-8XME CCD camera was used (OPAO). For the TCfA C60, a combination of Johnson and Causins filters was used. TCfA SC had non-standard filters with effective wavelength midpoints similar to the Johnson system. In OPAO, the standard Johnson system was used.

For CCD reduction and the measurement of instrumental magnitudes, IRAF packages were used. Our observations began in March 2007, long before the eclipse. Unfortunately, even though they lasted for about four years, the 4th contact was missed due to technical difficulties and unfavourable weather conditions. Because the atmospheric extinction was not estimated, and there was no transfor-

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mation to the Standard System, the data was inconsistent. This is visible as a shift between the observations from different telescopes (see Fig. 1). This shift is different in every filter. As it would be expected, the shift is smallest for the V filter and largest for the R filter, where the differences in the implementation of the photometric band are quite large.

CALIBRATION OF INSTRUMENTAL MAGNITUDES

In this paper, the correction for atmospheric extinction and the transformation to the Standard System for data from the TCfA C60 telescope, are presented. Unfortunately, the same transformation could not be performed for data from the other two telescopes, due to technical issues. The first step taken to improve the data, was estimating atmospheric extinction. While this problem is often ignored due to insignificant effects on results, in this case the effects were noticeble. With the TCfA SC telescope, a wide-field observation of stars was made, hence stars that were used for comparison were far away. Because of this, extinction was different for every star, rendering the comparison between them useless. In the case with the other two telescopes, small-field observations were carried out. In these fields, it was impossible to use the same comparison stars, as were used for the TCfA SC telescope. Instead, the only option was to use comparison stars with different color indices, therefore the 2nd order extinction coefficient was important. To calculate this effect, the formula of Buchheim was used [2]:

$$(B-V) = (b-v) - k'_{bv}X - k''_{bv}(b-v)X, \qquad (1)$$

$$V = v - k'_v X - k''_v (B-V)X, \qquad (2)$$

where V is observed magnitude , v is instrumental magnitude , k'_i is the 1st-order extinction coefficient, k''_i is the 2nd-order extinction coefficient, and X is the airmass. Corresponding equations with permutation of symbols and $(V-R_c)$ color index used for determining R_c second order extinction coefficient, can be applied to observations in all filters. M67 was used as a standard field of stars, and magnitudes from Benson [1] were used. After observing the standard field of stars several times during the night at significantly different airmasses, we were able to estimate extinction coefficients for Torun, which are shown in Table 1.

Table 1: Estimated extinction coefficients for Torun

filter	1st order coefficient	2nd order coefficient
B	0.462	-0.0659
V	0.275	0.0038
R_c	0.167	0.0085

The optical systems of every telescope differ. To minimize effect of these differences, we transferred our observations to the standard system as a next step of the calibration process. To do this, we used the same standard field of stars with known magnitudes, and formulas from Benson [1]:

$$\Delta(B-V)_0 = \Delta(B-V)T_{bv}, \qquad (3)$$

$$\Delta(V-R)_0 = \Delta(V-R_c)T_{vr}, \qquad (4)$$

$$\Delta V_0 = \Delta V + \Delta(V-R)_0 T_v, \qquad (5)$$

where V_0 is the magnitude in the standard system, and T_i is the transformation coefficient. Following this, we used these coefficients (see Table 2) to transform our ε Aur observations to the standard system.

Table 2: Estimated transformation coefficients for TCfA C60

T_{bv}	T_{vr}	T_v
1.05	1.37	0.029

RESULTS

After transforming observations to the standard system, our data matched better with the rest of international campaign data (see Fig. 2). Thanks to this, our observations can be added to observations from all over the world, creating the possibility to compare great amounts of data. Transformed magnitudes carried out with the TCfA C60 telescope are presented in Table 3. Not transformed magnitudes carried out with the OPAO and the TCfA SC telescopes, are presented in Table 4 and Table 5.

REFERENCES

[1] Benson P. J. 1998, International Amateur-Professional Photoelectric Photometry Communication, 72, 42

[2] Buchheim B. 2005, Society for Astronomical Sciences Annual Symposium, 24, 111

[3] Guinan E. F. & Dewarf L. E. 2002, ASP Conf. Series, 279, 121

[4] Hopkins J. L. 2011, Epsilon Aur Campaign Newsletters, `www.hposoft.com/EAur09/NL09/NL24.pdf`

[5] Tomov T., Wychudzki P., Mikołajewski M. et al. 2012, Bulgarian Astronomical Journal, 18, 3

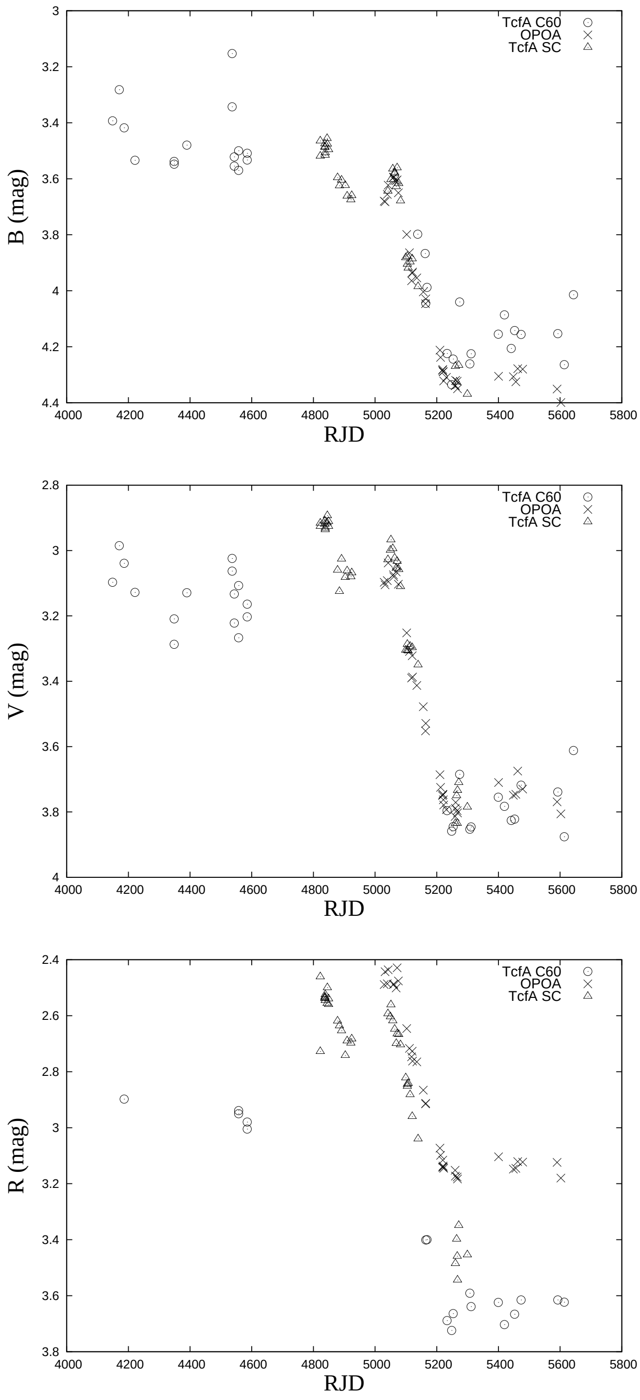

Fig. 1: BVR observations of 2009-2011 ε Aur eclipse from Torun and Olsztyn. In all the filters shift between the observations from different telescopes appeared. The smallest shift is in the V filter and biggest in the R filter.

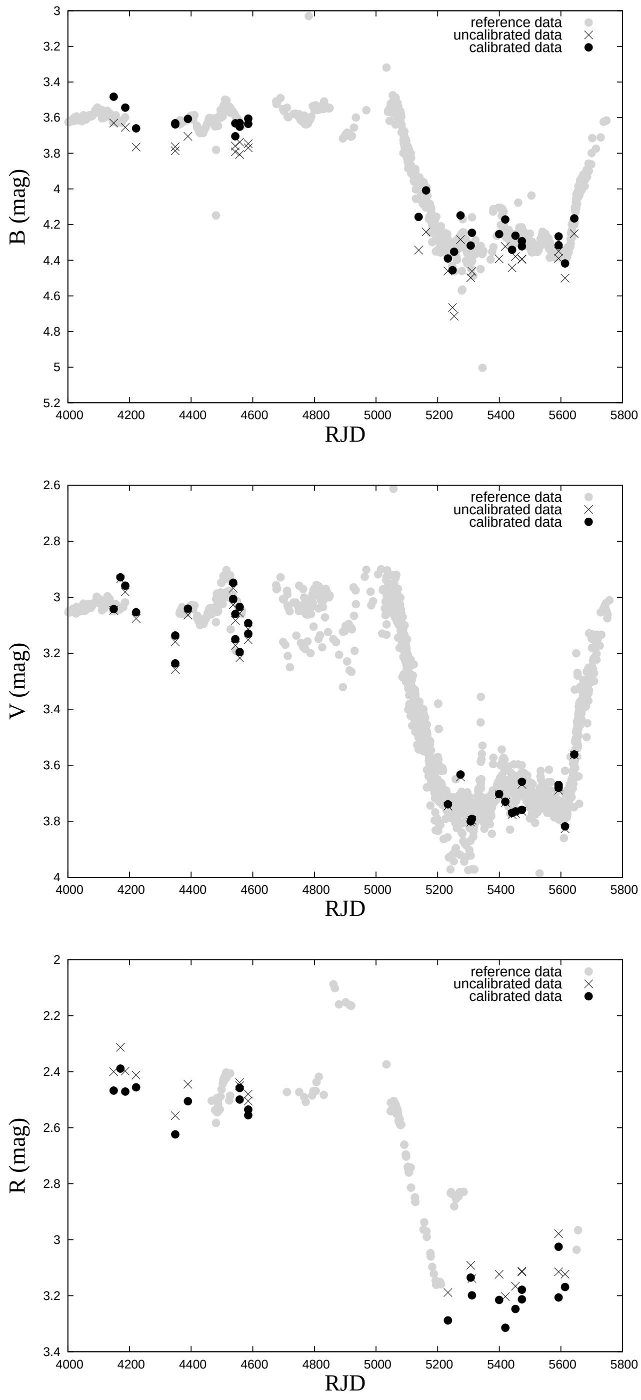

Fig. 2: Data form the TCfA C60 telescope after correction for atmospheric extinction and transformation to the Jonson's Standard System, compared with uncalibrated data and reference data from the International ε Aurigae Campaign 2009 website[2]. Data after transformation match better with observations from the international campaign.

[2] `http://www.hposoft.com/Campaign09.html`

Table 3: Magnitudes from observations carried out with the TCfA C60 telescope, after calibration.

HJD	B	σ_B	HJD	V	σ_V	HJD	R	σ_R
2455138.31401	4.157	0.059	2455138.30936	4.003	0.036	2455233.21425	3.288	0.073
2455162.46438	4.01	0.08	2455162.45981	4.06	0.05	2455248.30380	4.128	0.017
2455233.21075	4.39	0.05	2455233.21425	3.74	0.05	2455253.34184	4.173	0.026
2455248.31192	4.456	0.032	2455248.30380	4.403	0.029	2455307.25708	3.135	0.103
2455253.34887	4.352	0.056	2455253.34184	4.460	0.031	2455311.32045	3.199	0.087
2455274.27744	4.148	0.198	2455274.28303	3.633	0.175	2455399.56050	3.215	0.185
2455307.25046	4.317	0.082	2455307.25708	3.80	0.133	2455419.50232	3.315	0.061
2455311.31344	4.246	0.066	2455311.32045	3.791	0.08	2455452.40641	3.247	0.079
2455399.54445	4.254	0.128	2455399.56050	3.703	0.167	2455473.44830	3.213	0.081
2455419.49615	4.171	0.109	2455419.50232	3.730	0.104	2455473.46063	3.179	0.079
2455441.45966	4.34	0.09	2455441.46528	3.770	0.113	2455592.29266	3.21	0.16
2455452.40178	4.262	0.154	2455452.40641	3.765	0.105	2455592.30648	3.025	0.114
2455473.44424	4.322	0.095	2455473.44830	3.659	0.087	2455613.29602	3.169	0.049
2455473.46440	4.293	0.137	2455473.46063	3.759	0.095	2454148.53502	2.468	0.032
2455592.28726	4.315	0.113	2455592.29266	3.681	0.109	2454170.42009	2.389	0.037
2455592.31022	4.267	0.134	2455592.30648	3.670	0.093	2454186.41900	2.471	0.042
2455613.29350	4.42	0.05	2455613.29602	3.818	0.038	2454221.32335	2.456	0.025
2455643.33223	4.165	0.128	2455643.34189	3.561	0.118	2454348.47469	2.62	0.04
2454148.53212	3.482	0.024	2454148.53502	3.042	0.031	2454389.44690	2.506	0.029
2454170.42282	3.387	0.039	2454170.42009	2.929	0.025	2454557.41097	2.499	0.036
2454186.42211	3.544	0.027	2454186.41900	2.959	0.027	2454557.42697	2.458	0.046
2454221.32704	3.660	0.026	2454221.32335	3.054	0.026	2454585.33780	2.556	0.049
2454348.45764	3.631	0.033	2454348.46992	3.236	0.037	2454585.35393	2.535	0.036
2454348.46436	3.638	0.041	2454348.47469	3.137	0.039			
2454389.44264	3.607	0.036	2454389.44690	3.041	0.037			
2454536.45994	3.155	0.041	2454536.47341	2.948	0.039			
2454536.48185	3.391	0.041	2454536.48880	3.006	0.049			
2454543.38956	3.632	0.045	2454543.39670	3.150	0.042			
2454543.41103	3.704	0.034	2454543.40500	3.060	0.037			
2454557.40449	3.630	0.048	2454557.41097	3.035	0.031			
2454557.43275	3.651	0.032	2454557.42697	3.196	0.056			
2454585.33093	3.634	0.024	2454585.33780	3.130	0.034			
2454585.35980	3.6054	0.024	2454585.35393	3.092	0.042			

Table 4: Uncalibrated magnitudes, observations carried out with OPAO telescope.

HJD	B	σ_B	HJD	V	σ_V	HJD	R	σ_R
2455029.5289	3.680	0.015	2455029.5289	3.10	0.01	2455029.5289	2.489	0.015
2455032.5121	3.682	0.012	2455032.5121	3.105	0.017	2455032.5121	2.443	0.022
2455039.4844	3.656	0.017	2455039.4844	3.092	0.019	2455039.4844	2.486	0.016
2455042.5219	3.623	0.012	2455042.5219	3.038	0.025	2455042.5219	2.436	0.018
2455059.4160	3.595	0.013	2455059.4160	3.074	0.009	2455059.4160	2.489	0.018
2455060.4855	3.59	0.01	2455060.4855	3.08	0.01	2455060.4855	2.487	0.014
2455063.5310	3.606	0.022	2455068.4314	3.065	0.016	2455068.4314	2.501	0.01
2455068.4314	3.61	0.01	2455071.4617	3.046	0.012	2455071.4617	2.429	0.013
2455071.4617	3.604	0.015	2455075.4379	3.103	0.011	2455075.4379	2.476	0.011
2455075.4379	3.650	0.011	2455102.4174	3.252	0.006	2455102.4174	2.646	0.015
2455102.4174	3.799	0.007	2455111.3669	3.309	0.005	2455111.3669	2.717	0.006
2455111.3669	3.86	0.01	2455118.3833	3.390	0.012	2455118.3833	2.747	0.012
2455118.3833	3.964	0.008	2455120.4379	3.322	0.01	2455120.4379	2.727	0.011
2455120.4379	3.94	0.01	2455121.3976	3.387	0.008	2455121.3976	2.762	0.008
2455121.3976	3.93	0.02	2455135.3786	3.413	0.012	2455135.3786	2.765	0.013
2455135.3786	3.954	0.011	2455156.3841	3.478	0.006	2455156.3841	2.866	0.011
2455156.3841	4.004	0.005	2455163.3573	3.552	0.013	2455163.3573	2.915	0.005
2455163.3573	4.046	0.009	2455164.3766	3.53	0.02	2455164.3766	2.913	0.011
2455164.3766	4.029	0.007	2455210.3225	3.686	0.006	2455210.3225	3.073	0.006
2455210.3225	4.212	0.007	2455212.3733	3.725	0.006	2455212.3733	3.099	0.003
2455212.3733	4.238	0.014	2455218.4208	3.750	0.005	2455218.4208	3.141	0.005
2455218.4208	4.284	0.006	2455219.4222	3.746	0.004	2455219.4222	3.116	0.006
2455219.4222	4.281	0.005	2455220.3973	3.747	0.004	2455220.3973	3.137	0.004
2455220.3973	4.289	0.005	2455221.4129	3.763	0.005	2455221.4129	3.141	0.005
2455221.4129	4.29	0.01	2455222.4291	3.779	0.007	2455222.4291	3.15	0.01
2455222.4291	4.322	0.006	2455231.4778	3.793	0.004	2455259.4095	3.152	0.006
2455231.4778	4.309	0.013	2455259.4095	3.814	0.007	2455260.2333	3.173	0.002
2455259.4095	4.339	0.008	2455260.2333	3.789	0.009	2455266.2337	3.176	0.007
2455260.2333	4.338	0.006	2455261.2555	3.771	0.035	2455267.2611	3.183	0.006
2455261.2555	4.320	0.009	2455266.2337	3.796	0.009	2455400.4601	3.104	0.022
2455266.2337	4.323	0.005	2455267.2611	3.803	0.009	2455448.5372	3.148	0.007
2455267.2611	4.350	0.005	2455400.4601	3.710	0.015	2455456.4335	3.145	0.007
2455400.4601	4.305	0.021	2455448.5372	3.749	0.007	2455462.3898	3.121	0.009
2455448.5372	4.307	0.008	2455456.4335	3.746	0.005	2455478.6444	3.12	0.01
2455456.4335	4.325	0.007	2455462.3898	3.675	0.011	2455590.2297	3.124	0.005
2455462.3898	4.278	0.009	2455478.6444	3.730	0.007	2455602.4661	3.180	0.004
2455478.6444	4.280	0.014	2455590.2297	3.769	0.004			
2455590.2297	4.351	0.007	2455602.4661	3.806	0.009			
2455602.4661	4.40	0.01						

Table 5: Magnitudes calibrated only on extinction, from observations carried out with TCfA SC telescope. Filters, bandpasses had a rectangular shape, had effective wavelength midpoints $\lambda_B = 4510$ Å, $\lambda_V = 5380$ Å, $\lambda_R = 6360$ Å, and FWHMs of bandpasses $FWHM_B = 1235$ Å, $FWHM_V = 800$ Å, $FWHM_R = 1010$ Å.

HJD	B	σ_B	HJD	V	σ_V	HJD	R	σ_R
2454822.2981	3.465	0.031	2454822.2981	2.926	0.013	2454822.2981	2.728	0.383
2454822.3242	3.519	0.024	2454822.3242	2.916	0.016	2454822.3242	2.461	0.061
2454837.2718	3.488	0.006	2454837.2718	2.919	0.006	2454837.2718	2.533	0.009
2454837.2453	3.475	0.002	2454837.2453	2.910	0.009	2454837.2453	2.539	0.013
2454837.2908	3.486	0.007	2454837.2908	2.910	0.005	2454837.2908	2.536	0.011
2454838.2279	3.507	0.005	2454838.2279	2.931	0.005	2454838.2279	2.546	0.007
2454838.2467	3.516	0.006	2454838.2467	2.936	0.007	2454838.2467	2.53	0.02
2454844.3101	3.456	0.004	2454844.3101	2.915	0.009	2454844.3101	2.556	0.014
2454845.2553	3.476	0.002	2454845.2553	2.893	0.002	2454845.2553	2.500	0.003
2454849.2182	3.496	0.005	2454849.2182	2.926	0.011	2454849.2182	2.560	0.008
2454878.2895	3.596	0.004	2454884.2826	2.911	0.007	2454884.2826	2.540	0.012
2454884.2826	3.625	0.003	2454878.2895	3.060	0.004	2454878.2895	2.619	0.003
2454891.2363	3.605	0.002	2454884.2826	3.125	0.004	2454884.2826	2.636	0.004
2454903.2630	3.624	0.004	2454891.2363	3.026	0.002	2454891.2363	2.654	0.003
2454909.2763	3.662	0.005	2454903.2630	3.082	0.028	2454903.263	2.74	0.02
2454921.2998	3.675	0.004	2454909.2763	3.062	0.003	2454909.2763	2.690	0.003
2454924.2987	3.660	0.007	2454921.2998	3.080	0.005	2454921.2998	2.698	0.005
2455041.5250	3.644	0.008	2454924.2987	3.068	0.003	2454924.2987	2.683	0.002
2455051.4955	3.603	0.008	2455041.5250	3.028	0.014	2455041.525	2.593	0.019
2455057.5071	3.565	0.005	2455063.5368	2.999	0.012	2455063.5368	2.604	0.012
2455063.5368	3.582	0.004	2455051.4955	2.967	0.006	2455051.4955	2.561	0.008
2455063.5464	3.578	0.005	2455057.5071	2.994	0.008	2455057.5071	2.618	0.008
2455068.5066	3.628	0.004	2455063.5368	3.023	0.006	2455063.5368	2.648	0.008
2455071.5356	3.561	0.005	2455068.5066	3.054	0.004	2455068.5066	2.699	0.004
2455076.5512	3.617	0.007	2455071.5356	3.033	0.005	2455071.5356	2.665	0.004
2455082.4352	3.679	0.005	2455076.5512	3.058	0.008	2455076.5512	2.667	0.008
2455099.4106	3.882	0.005	2455082.4352	3.110	0.009	2455082.4352	2.704	0.013
2455104.4115	3.905	0.005	2455099.4106	3.305	0.008	2455099.4106	2.822	0.007
2455104.4430	3.877	0.005	2455104.4115	3.305	0.005	2455104.4115	2.852	0.004
2455107.4032	3.919	0.004	2455104.443	3.287	0.005	2455104.4430	2.845	0.004
2455113.4611	3.897	0.004	2455107.4032	3.307	0.004	2455107.4032	2.842	0.004
2455120.4109	3.886	0.009	2455113.4611	3.293	0.005	2455113.4611	2.88	0.01
2455139.3680	3.985	0.007	2455120.4109	3.297	0.007	2455120.4109	2.960	0.005
2455260.3047	4.270	0.028	2455139.3680	3.350	0.007	2455139.3680	3.040	0.011
2455264.2699	4.326	0.011	2455260.3047	3.835	0.141	2455260.3047	3.485	0.034
2455266.2867	4.469	0.003	2455264.2699	3.750	0.008	2455264.2699	3.398	0.009
2455267.2484	4.559	0.005	2455266.2867	3.835	0.004	2455266.2867	3.459	0.004
2455271.3038	4.266	0.014	2455267.2484	3.734	0.003	2455267.2484	3.544	0.005
2455299.2975	4.369	0.008	2455271.3038	3.710	0.006	2455271.3038	3.349	0.006
2455299.2975	3.785	0.005	2455299.2975	3.454	0.008			