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CCD photometry of CY Aquarii IV. The 2012–2015 seasons

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Abstract

Based on more than 50 partial nights of CCD monitoring, we derive 118 new times of maximum light of the SX Phoenicis star CY Aquarii. These times support a linear ephemeris for 2013–2015.

Keywords: technique: photometric – stars: individual: CY Aqr – variable stars: SX Phoenicis stars – variable stars: period change

1 Introduction

CY Aquarii (BD +00°4900) is a short-period ($P = 87.9$ min), large-amplitude ($0\overset{\mathrm{m}}{.}71$ in V) SX Phoenicis star. Since the discovery of its variability in 1934, this pulsating star has been extensively observed, and several investigations of its changing pulsation period using the $O-C$ diagram have been published.

This is our fourth data paper presenting a set of new times of maximum of CY Aqr. Previous papers are Tuvikene et al. (2010) [Paper I] and Sterken et al. (2011, 2012) [Paper II, III]. The present paper gives a set of more than 20 000 differential magnitudes and 118 new timings obtained in 2012–2015, and provides an updated linear ephemeris for 2013–2015.

2 Observations

All photometric data reported in this paper were obtained through CCD imaging obtained over more than 50 partial nights comprising a total of more than 20 000 useful CCD frames. Table 1 gives the journal of observations.

2.1 Observations at Bosscha Observatory

CCD frames of CY Aqr with its comparison stars were obtained by S. K. Nugroho on October 12, 2012 with the SBIG ST8-XME and on October 13–16, 2012 with the SBIG ST9 CCD cameras in the V band on the Gunma Astronomical Observatory Institute of Technology Bandung Remote Telescope System (20-cm $f/10.0$) at Bosscha Observatory, Indonesia. Integration time was 40 seconds and 60 seconds, respectively, with 2×2 binning. For a complete description of this work, we refer to Nugroho (2013).

2.2 Observations at the Nikolaus Cusanus Gymnasium Bruneck

The observations were obtained from a roll-off-roof observatory located at a 1600-m altitude site near Bruneck (Südtirol, Italy). The observations were obtained by C. Wiedemair and a team of students. A 10-inch Meade LX200 telescope with an SBIG ST8-XME CCD camera was used. Exposure time was 15 s, with 2×2 binning, and no filter was used. Flat-field frames were obtained by taking 7-second exposures of a light foil placed in front of the telescope aperture. Data frames were calibrated with nightly-averaged master darks and flats.

2.3 Observations at Tartu Observatory

At Tartu Observatory, two telescopes were used by T. Eenmäe. In 2014, an automatic 12.5-inch $f/8$ PlaneWave Instruments CDK reflector equipped with an Apogee Alta U42 CCD camera was used. Observations were done with an Astrodon Photometrics dielectric-type Johnson-Cousins R band filter using 30-second exposures. For calibration, in addition to bias- and dark frames, 13-second twilight flat field frames were taken. Master bias- and dark frames were averages of 124 individual frames.

In 2015, a 0.6-m $f/12.5$ Zeiss 600 reflector was used. This telescope is equipped with Andor Ikon-L DZ936-BV CCD-camera and observations were done with an Optec Inc glass-type Bessell V band filter using 30-second exposures. To calibrate the data, only bias frames and 30-second twilight sky flat field frames were taken. To ensure the best photometric quality, filters were not changed in between flat-field and target exposures.

2.4 Observations at the iTelescope.Net telescope at New Mexico, USA

The instrument is a 0.25-m $f/3.4$ reflector located at Mayhill, New Mexico (elevation 2225 m, 32°.9 N, 105°.5 W). Observer T. Tuvikene used a V filter during the first night, and worked filterless during the second night.

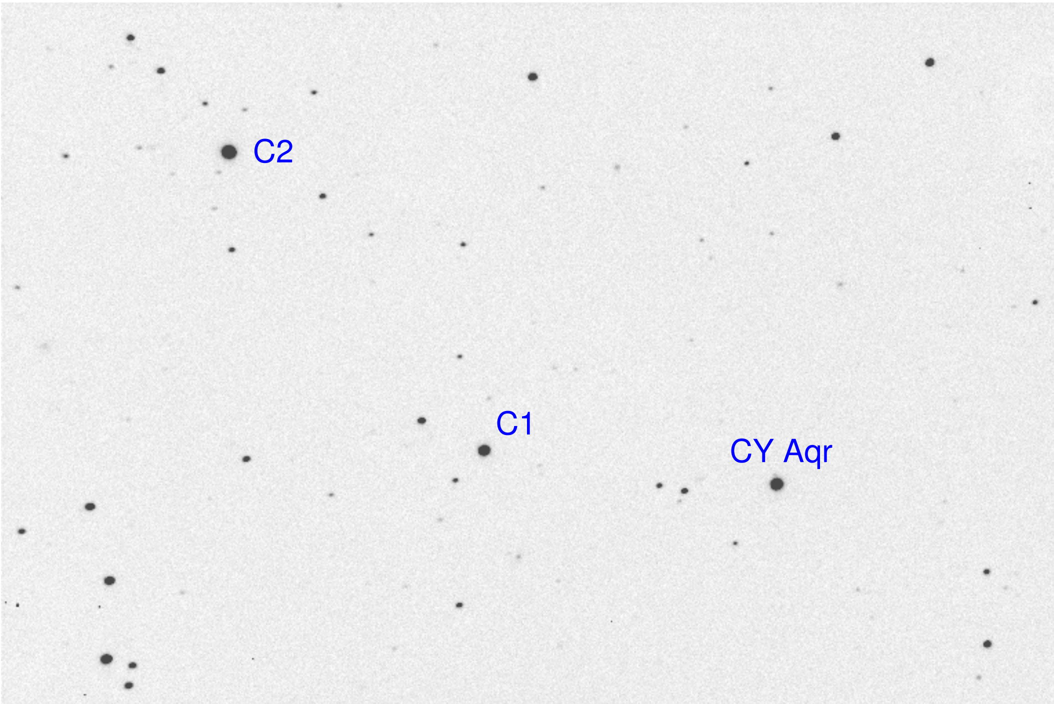

Figure 1: CY Aqr CCD field, replicated from Sterken et al. (2011). North is up and East is left, field of view is 18′ × 12′. CY Aqr and the comparison stars C_1 = GSC 00567–01826 and C_2 = GSC 00567-02036 are marked.

2.5 Observations at the iTelescope.Net telescope at Siding Spring Observatory, Australia

The instrument is a 0.32-m $f/9$ reflector equipped with a $f/7$ focal reducer at Siding Spring Observatory (elevation 1122 m, 31°.3, S 149°.1 E). A Luminance L filter (passband 400–750 nm) was used during all nights. Observations were carried out by C. Wiedemair.

3 Data reduction

Data reduction at Bosscha Observatory was done by S. K. Nugroho using aperture photometry in the IRAF reduction package. An aperture radius of 1 FWHM was used.

All other CCD magnitudes were extracted by T. Tuvikene by means of aperture photometry via routines in the IDL Astronomy User's Library[1] in a workflow as described by Tuvikene (2012). Aperture size was scaled with the full width at half maximum (FWHM) of the stellar image, and an aperture radius of 1.6×FWHM was used for all frames, see also Tuvikene & Sterken (2010).

The data in this paper (20 971 differential magnitudes of CY Aqr and of the compar-

[1] http://idlastro.gsfc.nasa.gov/

ison stars) are presented as differential light curves relative to C_1 = GSC 00567–01826 as comparison star. Differential magnitudes of the comparison stars are given to assess the observational precision of our data. The average differential magnitude of the comparison stars is listed in Table 2.

All differential magnitudes of CY Aqr and of the two comparison stars are given in online Tables `2012-bosscha.dat`, `2012-bruneck.dat`, `2012-itusa-clear.dat`, `2012-itusa-V.dat`, `2013-bruneck.dat`, `2013-itsso.dat`, `2014-bruneck.dat`, `2014-tartu.dat`, `2015-bruneck.dat` and `2015-tartu.dat`.

4 The times of maximum

Times of maximum light were determined from visual inspection of the light curves within $\pm 0\overset{\mathrm{d}}{.}005$ of the moment of maximum light, supported by a moving-average line. Relative weights were assigned using the same criteria as used in Tuvikene et al. (2010), see Table 3. Table 5 lists the results, with corresponding weight factors and cycle number E.

During the 2015 season six maxima have been simultaneously covered from Tartu (V band) as well as from Bruneck (no filter used). The average difference between the derived times of maximum is $0\overset{\mathrm{d}}{.}0001$ with a standard deviation $\sigma = 0\overset{\mathrm{d}}{.}0003$ (i.e., less than half a minute). This result illustrates the coherence of the set of visually-determined times of maximum, as well as the fact that the different spectral responses of the telescope-camera systems (i.e., the various CCD detectors, V and R filters) do not lead to any appreciable differences in the times of maximum light.

5 Ephemeris and resulting *O-C* diagrams

The set of 105 new times of maximum obtained in 2013–2015 leads to a linear ephemeris for 2013–2015:

$$\begin{array}{rcrcl} T_{\max} & = & 2426159.4714 & + & 0.061038430\,E \\ & & \pm 0.0006 & & \pm 0.000000005 \end{array} \qquad (1)$$

The pulsation period in Eq. (1) is formally slightly shorter than the ones given by Papers II and III, see also Table 4.

6 Discussion

Figure 2 shows the new $O-C$ points overplotted in Fig. 3 of Fu & Sterken (2003) (ephemeris $T_{\max} = 2426159.4967 + 0.0610383716E$) together with $O-C$ values of Papers II and III, and of the present paper.

The average $O-C$ with respect to Eq. (1) amounts to 0.0043 ± 0.0012 for 2012, a value that is significantly positive. Moreover, the standard deviation of the 2012 $O-C$ values (0.00034 for the Bruneck data) is twice as high as the corresponding standard deviations in

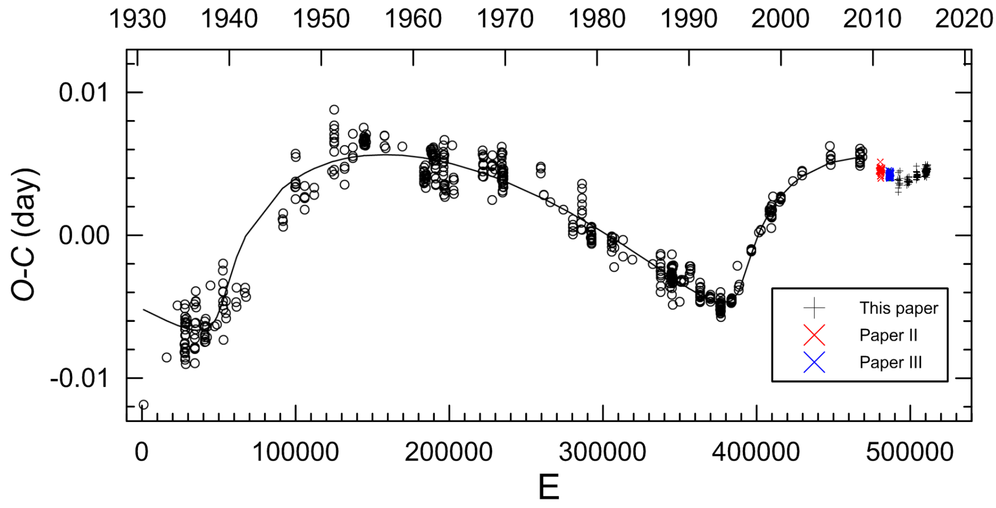

Figure 2: $O-C$ curve with respect to ephemeris (1) of Fu & Sterken (2003). Full line and $\circ$: light-time orbit solution and data from Fu & Sterken (2003); $\times$: $T_{\max}$ from Papers II and III; $+$: all $T_{\max}$ listed in this paper. The upward slope of of the $O-C$ trend reported in this paper indicates that the actual period is shorter than the one used to construct the model.

the subsequent years 2013–2015. This means that the pulsation period most likely changed around 2013, but neither the onset of the change nor the duration (i.e., the "suddenness" of the period change) was captured. As stated in Tuvikene et al. (2010), it will require several more years of additional monitoring before any significant update to the any model can be considered.

Table 4 gives an overview of our linear ephemeris formulae for CY Aqr. Our data confirm that modest equipment, supported by adequate training and tutoring – when sustained for at least 5 to 10 years – will provide enough evidence to conclude whether a binary model can fully account for all the period variability observed in this star.

Acknowledgments

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Table 1: Journal of observations: JD, number of CCD frames, average differential magnitude between comparison stars, and standard deviation σ for each nightly sequence.

JD−2400000	N	C_1–C_2	σ	Band	Site
56186.82 – .87	60	−1.008	0.013	V	iT USA 2012
56189.82 – .89	161	−1.038	0.007	–	iT USA 2012
56213.06 – .24	134	−1.021	0.031	V	Bosscha 2012
56214.12 – .26	181	−1.008	0.027	V	Bosscha 2012
56217.13 – .24	62	−1.026	0.026	V	Bosscha 2012
56247.29 – .36	161	−1.025	0.006	–	Bruneck 2012
56249.27 – .39	295	−1.028	0.008	–	Bruneck 2012
56253.27 – .35	220	−1.030	0.007	–	Bruneck 2012
56274.22 – .35	367	−1.031	0.006	–	Bruneck 2012
56281.20 – .30	253	−1.028	0.006	–	Bruneck 2012
56556.33 – .44	347	−1.027	0.008	–	Bruneck 2013
56559.28 – .44	381	−1.029	0.010	–	Bruneck 2013
56560.28 – .42	337	−1.027	0.005	–	Bruneck 2013
56609.25 – .37	197	−1.036	0.011	–	Bruneck 2013
56624.21 – .38	425	−1.039	0.008	–	Bruneck 2013
56629.21 – .33	309	−1.040	0.008	–	Bruneck 2013
56643.21 – .31	246	−1.034	0.007	–	Bruneck 2013
56571.91 – .94	63	−1.041	0.005	L	iT SSO 2013
56577.05 – .07	19	−1.045	0.005	L	iT SSO 2013
56585.89 – .98	96	−1.044	0.005	L	iT SSO 2013
56592.04 – .06	44	−1.044	0.005	L	iT SSO 2013
56619.96 – .98	36	−1.051	0.006	L	iT SSO 2013
56620.93 – .99	40	−1.051	0.008	L	iT SSO 2013
56621.00 – .02	29	−1.052	0.011	L	iT SSO 2013
56920.32 – .42	132	−1.055	0.009	R	Tartu 2014
56921.28 – .46	219	−1.053	0.009	R	Tartu 2014
56926.34 – .47	189	−1.058	0.011	R	Tartu 2014
56924.32 – .45	341	−1.050	0.005	–	Bruneck 2014
56928.27 – .47	633	−1.049	0.008	–	Bruneck 2014
56930.28 – .42	640	−1.060	0.008	–	Bruneck 2014
56949.25 – .45	932	−1.052	0.011	–	Bruneck 2014
56963.24 – .44	871	−1.046	0.016	–	Bruneck 2014
56985.27 – .36	402	−1.052	0.009	–	Bruneck 2014
57252.40 – .53	299	−1.024	0.004	V	Tartu 2015
57258.34 – .56	507	−1.022	0.008	V	Tartu 2015
57276.30 – .49	448	−1.018	0.007	V	Tartu 2015
57295.25 – .50	582	−1.020	0.005	V	Tartu 2015
57307.23 – .40	409	−1.017	0.003	V	Tartu 2015
57322.19 – .41	519	−1.017	0.006	V	Tartu 2015
57287.29 – .38	414	−1.056	0.008	–	Bruneck 2015
57295.35 – .43	391	−1.055	0.015	–	Bruneck 2015
57316.24 – .37	565	−1.049	0.008	–	Bruneck 2015
57316.37 – .43	262	−1.049	0.009	–	Bruneck 2015
57317.24 – .35	509	−1.055	0.009	–	Bruneck 2015
57317.35 – .41	256	−1.041	0.009	–	Bruneck 2015
57322.26 – .47	973	−1.042	0.012	–	Bruneck 2015
57328.23 – .33	555	−1.054	0.012	–	Bruneck 2015
57328.35 – .45	565	−1.050	0.018	–	Bruneck 2015
57329.22 – .31	395	−1.051	0.010	–	Bruneck 2015
57329.31 – .43	551	−1.042	0.011	–	Bruneck 2015
57332.20 – .30	440	−1.045	0.009	–	Bruneck 2015
57332.31 – .42	531	−1.041	0.009	–	Bruneck 2015
57345.21 – .33	551	−1.051	0.009	–	Bruneck 2015
57345.33 – .37	178	−1.039	0.011	–	Bruneck 2015
57359.18 – .28	455	−1.047	0.009	–	Bruneck 2015
57359.28 – .34	281	−1.045	0.011	–	Bruneck 2015
57363.19 – .31	265	−1.032	0.012	–	Bruneck 2015
57364.20 – .35	721	−1.048	0.010	–	Bruneck 2015
57367.18 – .28	422	−1.048	0.009	–	Bruneck 2015
57367.28 – .34	264	−1.044	0.011	–	Bruneck 2015

Table 2: Differential magnitudes of the comparison stars and mean error of the averages.

Site	Band	N	C_1–C_2
Bruneck	–	16901	-1.043 ± 0.002
Tartu	V	2764	-1.020 ± 0.001
Tartu	R	540	-1.056 ± 0.001
iT SSO	L	329	-1.047 ± 0.002
Bosscha	V	377	-1.018 ± 0.005
iT USA	V	60	-1.008

Table 3: Relative weights assigned to the T_{max} derived in this work.

Weight	Data density		Shape of maximum	Comment
1	very low		(ir)regular	
2	medium	+	irregular	
3	high	+	irregular	deviations from smoothness
4	medium	+	regular	
5	high	+	regular	smooth light curve

Table 4: Overview of our previously published linear ephemeris formulae for CY Aqr. Note that the mean errors for the interval 1930–2002 were not taken from the reference, but were calculated from the 544 maxima. The error in P is illusory because of the long-term wave.

Time base	T_0 (HJD)	$\pm$	P (days)	$\pm$	Reference
1930–2002	2426159.4967	0.0004	0.06103837	0.000000002	Fu & Sterken (2003)
2003–2009	2426159.512	0.001	0.061038349	0.0000000002	Paper I
2003–2010	2426159.5122	0.0005	0.061038349	0.0000000001	Paper II
2003–2011	2426159.5132	0.0001	0.0610383466	0.00000000003	Paper III
2013–2015	2426159.4714	0.0006	0.0610383430	0.00000000006	This work

Table 5: Times of maximum light (HJD − 2400000) of CY Aqr, weight W (see Table 3), and cycle number E. A digital version of this Table is included as file `tmax2012-15.dat`.

T_{max}	W	E	Band	Site	T_{max}	W	E	Band	Site
56186.8392	4	491942	*V*	iT USA 2012	57258.3684	5	509497	*V*	Tartu 2015
56189.8301	4	491991	–	iT USA 2012	57258.4291	5	509498	*V*	Tartu 2015
56213.0851	3	492372	*V*	Bosscha 2012	57258.4905	5	509499	*V*	Tartu 2015
56214.1231	3	492389	*V*	Bosscha 2012	57258.5517	4	509500	*V*	Tartu 2015
56214.1835	1	492390	*V*	Bosscha 2012	57276.3134	5	509791	*V*	Tartu 2015
56214.2459	1	492391	*V*	Bosscha 2012	57276.3746	5	509792	*V*	Tartu 2015
56247.3279	5	492933	–	Bruneck 2012	57276.4358	5	509793	*V*	Tartu 2015
56249.2814	5	492965	–	Bruneck 2012	57287.3007	4	509971	–	Bruneck 2015
56249.3421	5	492966	–	Bruneck 2012	57287.3617	5	509972	–	Bruneck 2015
56253.3101	5	493031	–	Bruneck 2012	57295.2968	5	510102	*V*	Tartu 2015
56274.2459	5	493374	–	Bruneck 2012	57295.2971	5	510102	–	Bruneck 2015
56274.3073	5	493375	–	Bruneck 2012	57295.3576	5	510103	*V*	Tartu 2015
56281.2662	5	493489	–	Bruneck 2012	57295.3581	3	510103	–	Bruneck 2015
56556.3651	5	497996	–	Bruneck 2013	57295.4185	4	510104	*V*	Tartu 2015
56556.4266	5	497997	–	Bruneck 2013	57295.4185	5	510104	–	Bruneck 2015
56559.2955	5	498044	–	Bruneck 2013	57295.4797	4	510105	*V*	Tartu 2015
56559.3563	5	498045	–	Bruneck 2013	57307.2601	5	510298	*V*	Tartu 2015
56559.4173	5	498046	–	Bruneck 2013	57307.3211	5	510299	*V*	Tartu 2015
56560.3329	5	498061	–	Bruneck 2013	57307.3821	5	510300	*V*	Tartu 2015
56560.3939	5	498062	–	Bruneck 2013	57316.2937	5	510446	–	Bruneck 2015
56571.9301	3	498251	*L*	iT SSO 2013	57316.3550	5	510447	–	Bruneck 2015
56577.0573	2	498335	*L*	iT SSO 2013	57316.4159	5	510448	–	Bruneck 2015
56585.9081	5	498480	*L*	iT SSO 2013	57317.2705	5	510462	–	Bruneck 2015
56585.9690	3	498481	*L*	iT SSO 2013	57317.3318	5	510463	–	Bruneck 2015
56609.3465	5	498864	–	Bruneck 2013	57317.3926	5	510464	–	Bruneck 2015
56620.9443	1	499054	*L*	iT SSO 2013	57322.2148	5	510543	*V*	Tartu 2015
56621.0050	4	499055	*L*	iT SSO 2013	57322.2755	5	510544	–	Bruneck 2015
56624.2401	5	499108	–	Bruneck 2013	57322.2757	5	510544	*V*	Tartu 2015
56624.3011	3	499109	–	Bruneck 2013	57322.3364	5	510545	*V*	Tartu 2015
56624.3622	3	499110	–	Bruneck 2013	57322.3365	5	510545	–	Bruneck 2015
56629.2455	5	499190	–	Bruneck 2013	57322.3975	5	510546	–	Bruneck 2015
56629.3063	3	499191	–	Bruneck 2013	57322.3976	5	510546	*V*	Tartu 2015
56643.2229	5	499419	–	Bruneck 2013	57322.4583	4	510547	–	Bruneck 2015
56643.2840	3	499420	–	Bruneck 2013	57328.2574	5	510642	–	Bruneck 2015
56920.3989	4	503960	*R*	Tartu 2014	57328.3183	5	510643	–	Bruneck 2015
56921.3145	5	503975	*R*	Tartu 2014	57328.3795	4	510644	–	Bruneck 2015
56921.4366	4	503977	*R*	Tartu 2014	57328.4407	2	510645	–	Bruneck 2015
56924.3664	5	504025	–	Bruneck 2014	57329.2341	5	510658	–	Bruneck 2015
56924.4272	5	504026	–	Bruneck 2014	57329.2951	5	510659	–	Bruneck 2015
56926.3803	4	504058	*R*	Tartu 2014	57329.3559	5	510660	–	Bruneck 2015
56926.4421	3	504059	*R*	Tartu 2014	57329.4168	5	510661	–	Bruneck 2015
56928.3336	5	504090	–	Bruneck 2014	57332.2251	5	510707	–	Bruneck 2015
56928.3946	5	504091	–	Bruneck 2014	57332.2861	5	510708	–	Bruneck 2015
56928.4560	5	504092	–	Bruneck 2014	57332.3468	5	510709	–	Bruneck 2015
56930.2866	5	504122	–	Bruneck 2014	57332.4077	5	510710	–	Bruneck 2015
56930.3476	5	504123	–	Bruneck 2014	57345.2260	5	510920	–	Bruneck 2015
56930.4090	5	504124	–	Bruneck 2014	57345.2870	5	510921	–	Bruneck 2015
56949.2700	5	504433	–	Bruneck 2014	57345.3481	5	510922	–	Bruneck 2015
56949.3309	5	504434	–	Bruneck 2014	57359.2040	5	511149	–	Bruneck 2015
56949.3917	5	504435	–	Bruneck 2014	57359.2652	5	511150	–	Bruneck 2015
56949.4528	5	504436	–	Bruneck 2014	57359.3259	4	511151	–	Bruneck 2015
56963.2477	5	504662	–	Bruneck 2014	57363.2326	5	511215	–	Bruneck 2015
56963.3085	5	504663	–	Bruneck 2014	57363.2935	4	511216	–	Bruneck 2015
56963.3697	5	504664	–	Bruneck 2014	57364.2091	5	511231	–	Bruneck 2015
56963.4307	3	504665	–	Bruneck 2014	57364.2704	5	511232	–	Bruneck 2015
56985.2823	5	505023	–	Bruneck 2014	57364.3315	5	511233	–	Bruneck 2015
56985.3434	5	505024	–	Bruneck 2014	57367.2000	5	511280	–	Bruneck 2015
57252.4473	5	509400	*V*	Tartu 2015	57367.2610	5	511281	–	Bruneck 2015
57252.5089	5	509401	*V*	Tartu 2015	57367.3220	5	511282	–	Bruneck 2015