Southern Eclipsing Binary Minima and Light Elements in 2019

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Abstract We present 156 times of minima of 68 southern hemisphere eclipsing binary stars acquired in 2019, plus two earlier (V676 Cen). These observations were acquired and analyzed by the authors who are members of the Southern Eclipsing Binary group of Variable Stars South (VSS) (http://www.variablestarssouth.org), using DSLR and CCD detectors. For seven of the systems we have derived updated light elements and present those as well as O–C values for the VSS minima. This paper is the fifth in a series; previous papers were published in the *Open European Journal on Variable Stars*.

1. Observations

Equipment and software used are set out in Table 1. Observer initials abbreviate the name of an author of this paper, surname last. Instrument refers to the telescope and objective diameter in cm, or to the DSLR camera used. Remaining columns refer to the software used for the purposes listed. See the References section of this paper for the software mentioned in this table.

All observers using PERANSO employed polynomial fitting for minima estimation. MINIMA25 takes the weighted mean and standard deviation of the means of six methods: parabolic fit, tracing paper, bisectors of chords, Kwee-van Woerden (Kwee and Van Woerden 1956), Fourier fit, and sliding integrations.

CCD or DSLR image sets were obtained in hours-long runs. Each observer analysed their own image sets as follows:

1. Calibrated them using bias frames, dark frames, and flat field frames.
2. Executed differential aperture photometric measurements on the calibrated sets.
3. Performed minima estimation on the photometric data.

This paper is the fifth in a series; previous papers were published in the *Open European Journal on Variable Stars* (Richards *et al.* 2016, 2017, 2018, 2019).

2. Results

Appendix A lists the minima estimates. Columns 1 and 2 list the GCVS designation and GCVS variability type of the target stars in lexical order of constellation abbreviation, as listed in (Samus *et al.* 2017). One entry refers to the ASAS-SN catalogue (Shappee *et al.* 2014). In some cases, more recent work may propose different variability types. Columns 3 and 4 record the heliocentric Julian dates of minima and the uncertainty (in days) as reported by the algorithm used in the photometry software. Column 5 lists the minimum type, primary (P) or secondary (S). We define the primary minimum as the deeper one in our observations where that can be determined, otherwise we assume the epoch recorded in the AAVSO Variable Star Index (Watson *et al.* 2006)—hereafter referred to as VSX—is of a primary minimum. Column 6 gives the filter used: B and V are Johnson *B* and *V*, or the transformed equivalent in the case of DSLR color sensors, R is Cousins *R*, and r' and i' are Sloan *r*' and *i*'. G is the green plane image from a tri-color DSLR camera. Column 7 gives the initials of the observer.

3. Analysis

Table 2 lists revised light elements for seven binaries in Appendix A. These are binaries for which we have derived four or more primary minima in 2019 and earlier years, spread over at least three observing seasons. (See Richards *et al.* 2016, 2017, 2018, 2019 for the earlier primary minima). Binaries with revised light elements reported in earlier papers in this series are excluded.

For these systems we derived new linear light elements by ordinary least squares regression. The regression used all the VSS primary minima times and the VSX epoch time as minima data. The VSX epoch and period were used to obtain an orbital cycle count for the minima data. By regressing the (HJD) minima times against cycles we obtained a best-fit period as the slope of the regression line, and a corrected zero epoch as the y-intercept at the earliest VSS minimum. The new zero epoch is the regressed value of the earliest VSS minimum.

Table 2 contains the resulting light elements for the systems we analysed. The first five columns list the system, the epoch

Table 1. Observers, equipment, and software.

Observer	*Instrument*	*Imaging*	*Calibration*	*Photometry*	*Minima*
TR	41 cm R-C + SBIG STXL-6303e	Maxim	Muniwin	Muniwin	peranso
MB	8-cm refractor +Atik One 6.0	Maxim	Maxim	Maxim	Maxim
MB	35-cm R-C + SBIG STT-3200	TheSkyx professional	Maxim	Maxim	Maxim
NB	Canon 650D	Maxim	Maxim	Maxim	Minima25e
RJ	25 cm GSO RCA + QSI-583 CCD.	Maxim	Maxim	Maxim	Minima25e

Notes: maxim dl (Diffraction Limited 2012); minima25 (Nelson, R. H. 2019); muniwin (Motl, D. 2011); peranso (Vanmunster 2013); theskyx professional (Software Bisque 2020).

Table 2. Revised linear light elements for systems with four or more VSS primary minima estimates, regressed from the VSX light elements.

Identifier	E_0	$E_{0_{err}}$	P	P_{err}	SD_{resid}	*No. Obs.*	*Interval*
YY Aps	2457505.114202	0.000659	0.85555536	2.69E-07	0.00145	4	1115
V0535 Ara	2456869.972074	0.000184	0.62930210	1.46E-08	0.00038	4	1818
BR Mus	2457439.073090	0.000910	0.79819773	1.45E-07	0.00232	6	1171
EZ Oct	2457504.118065	0.000270	0.28587823	3.66E-08	0.00065	5	1106
V0954 Sco	2457220.054859	0.004089	1.26858891	1.30E-06	0.00874	4	1464
RS Sgr	2455778.073564	0.000954	2.41568415	1.45E-07	0.00199	4	2911
FM Vel	2457446.001513	0.000865	0.38952718	2.90E-08	0.00196	5	1093

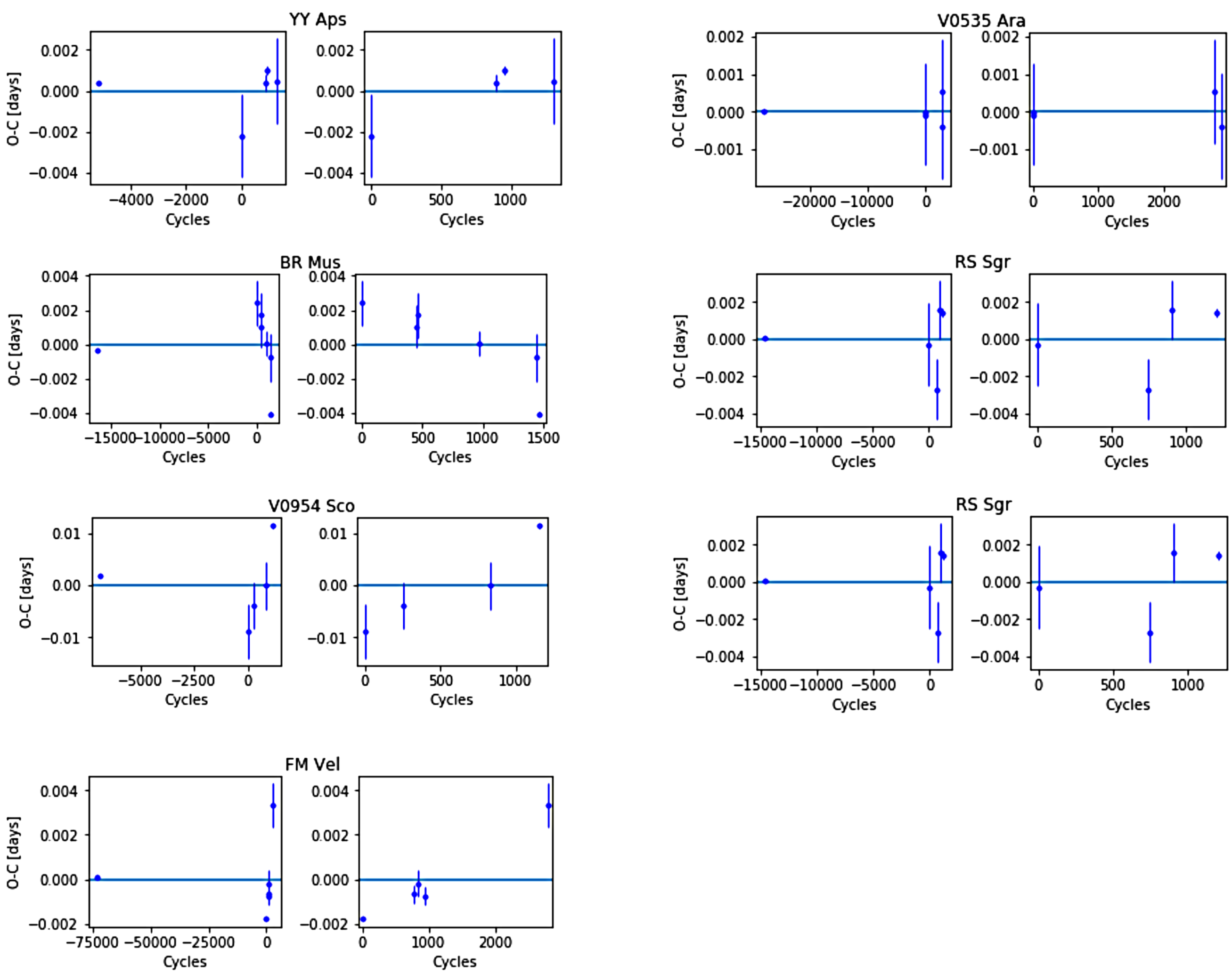

Figure 1. Residual (O–C) plots of the minima estimates against the light elements listed in Table 2. Left hand panels for each binary system show VSX and VSS minima, right hand panels the VSS minima only. Orbital cycle numbers count from zero at the first (regressed) VSS minimum, incrementing by the regressed period.

and standard error, and the period and standard error. The next column records the standard deviation of the residuals of the minima from the regression prediction. The smaller the number, the better are the minima data fitted to a linear fit (constant period). No. Obs is the number of VSS primary minima estimates used in the regression, and Interval is the time interval in days covered by them.

For each system in Appendix A, in Figure 1 we present plots of the residuals of the observed minima from the calculated regression (aka O–C values). The regression is the horizontal line at O–C = 0. The left-hand panel in each pair for a star shows (by the left edge) the VSX minimum, together with (near the right edge) the VSS minima. The latter are zoomed into in the right panel to exhibit any structure in the residuals which may indicate variation in the period. The error bars are those reported for the time of minimum by the software used for minima estimation.

The primary interest in the Table 2 light elements, and the Figure 1 residual plots, lies in indication of period change. The right-hand plots of BR Mus, V0954 Sco and FM Vel strongly indicate that a linear model is inadequate to represent the minima times. Those three systems also have the highest residual standard deviations. For the other systems the case for non-linear ephemerides is less clear. For them, however, it must be remarked that with the very large time gap between the original VSX epoch and those of the VSS, there could easily be non-linear models, e.g. sinusoidal or parabolic, that would fit the data shown. For a discussion on the problems of model fitting to minima data with large gaps, see the study of GZ Pup in Richards (2020).

The error bars in those plots are a poor indicator of the reliability of the individual minima estimates; since (as an informal study by TR has shown) different minima estimation algorithms can deliver error estimates differing by an order of magnitude on the same data. Implementations of the Kwee-Van Woerden algorithm (Kwee and van Woerden 1956) typically report a far smaller error than polynomial fits. For this reason and because VSX epoch data do not include errors, weighted linear regressions were not used in this study.

4. Conclusion

We have presented 158 minima estimates of 68 southern eclipsing binaries made by the authors in 2019, and a period analysis for seven of them where our data warrant it. In three cases there is a strong indication of period variability. It is outside the scope of this report to further investigate that, which requires mining the literature for earlier minima estimates and obtaining ongoing minima data acquisition in future years.

5. Acknowledgements

This research has made much use of the International Variable Star Index (VSX) database, operated at AAVSO, Cambridge, Massachusetts. (Watson *et al.* 2006).

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Appendix A: Minima estimates

Identifier	*Type*	*HJD of min.*	*Error*	*Min.*	*Filter*	*Observer*
II Aps	EW/KE	2458670.92385	0.00226	S	V	TR
MR Aps	EB	2458620.13966	0.00106	P	i'	TR
MR Aps	EB	2458624.09879	0.00261	S	i'	TR
MR Aps	EB	2458710.13585	0.00004	S	V	RJ
YY Aps	EB	2458619.90331	0.00206	P	r'	TR
YY Aps	EB	2458622.04136	0.00600	S	V	TR
V0535 Ara	EW	2458611.25151	0.00138	P	V	MB
V0535 Ara	EW	2458688.02545	0.00138	P	V	MB
V0610 Ara	EW	2458648.97530	0.00360	P	G	NB
V0878 Ara	EW:	2458654.97200	0.00380	S	V	NB
V0878 Ara	EW:	2458659.98090	0.00130	P	V	NB
V0625 Car	EW	2458601.99662	0.00039	S	V	MB
V0625 Car	EW	2458609.88956	0.00044	P	V	MB
V0625 Car	EW	2458610.02782	0.00047	S	V	MB
BH Cen	EB/KE	2458611.98856	0.00073	P	B	MB
BH Cen	EB/KE	2458611.98888	0.00070	P	I	MB
BH Cen	EB/KE	2458611.98891	0.00073	P	V	MB
BH Cen	EB/KE	2458613.17604	0.00096	S	B	MB
BH Cen	EB/KE	2458613.17616	0.00093	S	I	MB
BH Cen	EB/KE	2458613.17619	0.00093	S	V	MB
BH Cen	EB/KE	2458615.15530	0.00097	P	I	MB
BH Cen	EB/KE	2458615.15537	0.00109	P	B	MB
BH Cen	EB/KE	2458615.15540	0.00085	P	V	MB
V0676 Cen	EW/KW	2458241.06161	0.00012	P	r'	TR
V0676 Cen	EW/KW	2458241.20884	0.00006	S	r'	TR
V0676 Cen	EW/KW	2458580.97149	0.00054	S	r'	TR
V0676 Cen	EW/KW	2458581.11803	0.00064	P	r'	TR
V0676 Cen	EW/KW	2458581.26396	0.00063	S	r'	TR
V0701 Cen	EB/KE	2458609.12690	0.00140	P	G	NB
V0757 Cen	EW/KW	2458599.07912	0.00125	S	V	MB
V0757 Cen	EW/KW	2458599.25175	0.00135	P	V	MB
V0757 Cen	EW/KW	2458610.06147	0.00087	S	V	MB
V0757 Cen	EW/KW	2458610.23385	0.00126	P	V	MB
V0757 Cen	EW/KW	2458615.03940	0.00170	P	V	NB
V0758 Cen	EW/KE	2458611.01730	0.00380	P	V	NB
V0759 Cen	EW/RS	2458586.09960	0.00390	P	G	NB
V0759 Cen	EW/RS	2458658.97780	0.00370	P	V	NB
V0901 Cen	EW/RS	2458537.02129	0.00140	S	r'	TR
V1362 Cen	EW	2458657.95880	0.00220	P	G	NB
DM Cir	EW	2458654.13409	0.00113	P	V	MB
DM Cir	EW	2458656.06781	0.00100	P	V	MB
DM Cir	EW	2458657.03629	0.00134	S	V	MB
FQ CMa	EA+DSCT	2458531.05914	0.00055	P	V	MB
FQ CMa	EA+DSCT	2458548.08865	0.00233	S	V	MB
FQ CMa	EA+DSCT	2458847.04749	0.00060	P	B	MB
V0711 CrA	EB	2458729.94262	0.00062	P	V	NB
V0734 CrA	EA	2458712.04957	0.00079	P	V	MB
V0734 CrA	EA	2458713.02792	0.00078	P	V	MB
YY Eri	EW/KW	2458846.02929	0.00013	P	R	MB
YY Eri	EW/KW	2458846.99383	0.00012	P	R	MB
YY Eri	EW/KW	2458847.15406	0.00017	S	R	MB
DY Gru	EW/KW	2458674.19998	0.00086	P	R	MB
DY Gru	EW/KW	2458675.20866	0.00084	P	R	MB
DY Gru	EW/KW	2458678.06431	0.00097	S	R	MB
DY Gru	EW/KW	2458678.23237	0.00073	P	R	MB
DY Gru	EW/KW	2458776.01642	0.00099	P	V	MB
DY Gru	EW/KW	2458776.18324	0.00138	S	V	MB
V Gru	EW/KW	2458678.20098	0.00031	P	G	NB
V Gru	EW/KW	2458727.99620	0.00110	P	G	NB
V Gru	EW/KW	2458730.17521	0.00052	S	G	NB
SZ Hor	EW/KW	2458823.06965	0.00006	P	V	RJ
SZ Hor	EW/EK	2458828.07006	0.00006	P	V	RJ
BO Ind	EW	2458680.04546	0.00236	S	V	MB
BO Ind	EW	2458681.25973	0.00237	S	V	MB
BO Ind	EW	2458682.07175	0.00219	S	V	MB
BO Ind	EW	2458682.27209	0.00239	P	V	MB

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Appendix A: Minima estimates (cont.).

Identifier	*Type*	*HJD of min.*	*Error*	*Min.*	*Filter*	*Observer*
CU Ind	EW	2458735.02180	0.00087	S	R	MB
CU Ind	EW	2458735.18860	0.00099	P	R	MB
DD Ind	EW	2458728.16121	0.00069	S	V	MB
DD Ind	EW	2458729.97456	0.00072	S	V	MB
DD Ind	EW	2458730.15635	0.00072	P	V	MB
DD Ind	EW	2458731.96997	0.00133	P	R	MB
DD Ind	EW	2458731.97036	0.00126	P	I	MB
ST Ind	EW/KW	2458715.08663	0.00081	P	V	MB
ST Ind	EW/KW	2458728.95241	0.00077	S	V	MB
ST Ind	EW/KW	2458729.15346	0.00087	P	V	MB
TV Ind	EB	2458719.06029	0.00110	P	V	MB
TV Ind	EB	2458731.16962	0.00114	P	V	MB
GG Lup	EA	2458592.03938	0.00122	P	I	MB
GG Lup	EA	2458600.19409	0.00154	S	I	MB
GG Lup	EA	2458676.02807	0.00228	S	V	MB
RR Men	EA/D	2458516.13901	0.00150	P	r'	TR
XY Men	EB/KE	2458507.03335	0.00190	P	r'	TR
DG Mic	EA	2458707.02077	0.00032	P	V	NB
DI Mic	EA	2458686.05352	0.00146	S	r'	TR
BR Mus	EW/KE	2458586.08245	0.00137	P	r'	TR
BR Mus	EW/KE	2458610.02510	0.00008	P	V	RJ
BS Mus	EB/KE	2458576.07301	0.00018	P	V	RJ
eta Mus	EA	2458602.21272	0.00457	P	I	MB
eta Mus	EA	2458678.89444	0.00437	P	I	MB
TU Mus	EB/KE	2458556.03646	0.00020	S	V	RJ
TU Mus	EB/KE	2458617.07656	0.00016	S	V	RJ
TU Mus	EB/KE	2458619.15787	0.00012	P	V	RJ
TV Mus	EW/KW	2458575.09753	0.00150	P	r'	TR
TV Mus	EW/KW	2458580.22234	0.00120	S	r'	TR
TW Mus	EW/KW	2458538.24476	0.00121	S	r'	TR
V0398 Nor	EA	2458656.91950	0.00310	P	V	NB
EZ Oct	EW/KW	2458592.02865	0.00008	P	V	RJ
EZ Oct	EW/KW	2458592.17046	0.00007	S	V	RJ
EZ Oct	EW/KW	2458618.04283	0.00006	S	V	RJ
EZ Oct	EW/KW	2458756.97994	0.00005	S	V	RJ
EZ Oct	EW/KW	2458757.12349	0.00006	P	V	RJ
VV Ori	EA/KE	2458510.04224	0.00532	P	V	MB
ASASSN-V J184530.00-593235.0 (Pav)	EA:	2458711.12866	0.00191		R	MB
BF Pav	EW	2458701.99496	0.00036	S	R	MB
BF Pav	EW	2458702.14641	0.00041	P	R	MB
BF Pav	EW	2458710.91366	0.00051	P	R	MB
BF Pav	EW	2458711.06455	0.00053	S	R	MB
BF Pav	EW	2458713.93679	0.00075	P	V	MB
BF Pav	EW	2458713.93689	0.00077	P	R	MB
BF Pav	EW	2458713.93704	0.00086	P	I	MB
BF Pav	EW	2458714.08754	0.00075	S	I	MB
BF Pav	EW	2458714.08756	0.00082	S	V	MB
BF Pav	EW	2458714.08782	0.00073	S	R	MB
BF Pav	EW	2458716.96002	0.00042	P	V	MB
BF Pav	EW	2458717.11078	0.00050	S	V	MB
V0401 Pav	EW	2458621.06321	0.00061	P	r'	TR
V0401 Pav	EW	2458621.22654	0.00064	S	r'	TR
AD Phe	EW/KW	2458785.03012	0.00008	P	V	RJ
AD Phe	EW/KW	2458815.04430	0.00008	P	V	RJ
AE Phe	EW/KW	2458775.05009	0.00123	S	V	MB
BQ Phe	EW	2458780.07172	0.00010	S	V	RJ
GY Pup	EW/KW	2458517.08537	0.00800	P	r'	TR
GZ Pup	EW/KW	2458487.02517	0.00160	P	V	TR
GZ Pup	EW/KW	2458487.18540	0.00090	S	V	TR
GZ Pup	EW/KW	2458513.12673	0.00110	S	V	TR
HI Pup	EW/KW	2458490.05477	0.00150	P	V	TR
NO Pup	EA/KE:	2458494.97609	0.00461	S	R	MB
NO Pup	EA/KE:	2458498.12561	0.00134	P	R	MB
V0410 Pup	EB	2458488.02543	0.00611	S	R	MB
V0410 Pup	EB	2458494.15991	0.00505	S	R	MB
V0410 Pup	EB	2458548.04227	0.00393	P	R	MB

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Appendix A: Minima estimates (cont.).

Identifier	*Type*	*HJD of min.*	*Error*	*Min.*	*Filter*	*Observer*
V0653 Pup	EW	2458485.17682	0.00150	S	r'	TR
V0653 Pup	EW	2458486.14701	0.00150	P	r'	TR
CP Scl	EW	2458778.05987	0.00073	S	V	MB
CP Scl	EW	2458778.21715	0.00098	P	V	MB
CW Scl	EW	2458779.05251	0.00087	S	V	MB
UY Scl	EW	2458759.18866	0.00065	S	V	MB
UY Scl	EW	2458760.10020	0.00056	P	V	MB
UY Scl	EW	2458775.03874	0.00048	P	V	MB
UY Scl	EW	2458775.94910	0.00064	S	V	MB
UY Scl	EW	2458776.13181	0.00068	P	V	MB
V0760 Sco	EA/DM	2458714.98705	0.00022	P	V	NB
V0954 Sco	EB	2458684.01785	0.00038	P	V	NB
RS Sgr	EA/SD	2458688.97438	0.00024	P	V	NB
V2509 Sgr	EB/KE	2458610.17480	0.00630	S	G	NB
V2509 Sgr	EB/KE	2458683.02100	0.00220	S	V	NB
QW Tel	EW	2458681.02766	0.00051	P	V	NB
V0343 Tel	EB	2458705.97525	0.00055	P	V	NB
GN TrA	EA/KE	2458701.06456	0.00218	S	V	MB
GN TrA	EA/KE	2458714.89195	0.00087	P	V	MB
AQ Tuc	EW	2458739.02394	0.00020	S	V	RJ
BU Vel	EW	2458515.04053	0.00120	P	V	TR
FM Vel	EW/KW	2458506.10282	0.00110	S	r'	TR
FM Vel	EW/KW	2458538.04364	0.00100	S	r'	TR
FM Vel	EW/KW	2458539.01810	0.00100	P	r'	TR
FM Vel	EW/KW	2458539.21201	0.00090	S	r'	TR
V0362 Vel	EW	2458610.01938	0.00013	S	G	NB