Looking for Sub-stellar Companions in the Eclipse Timing Variations of PCEB Systems

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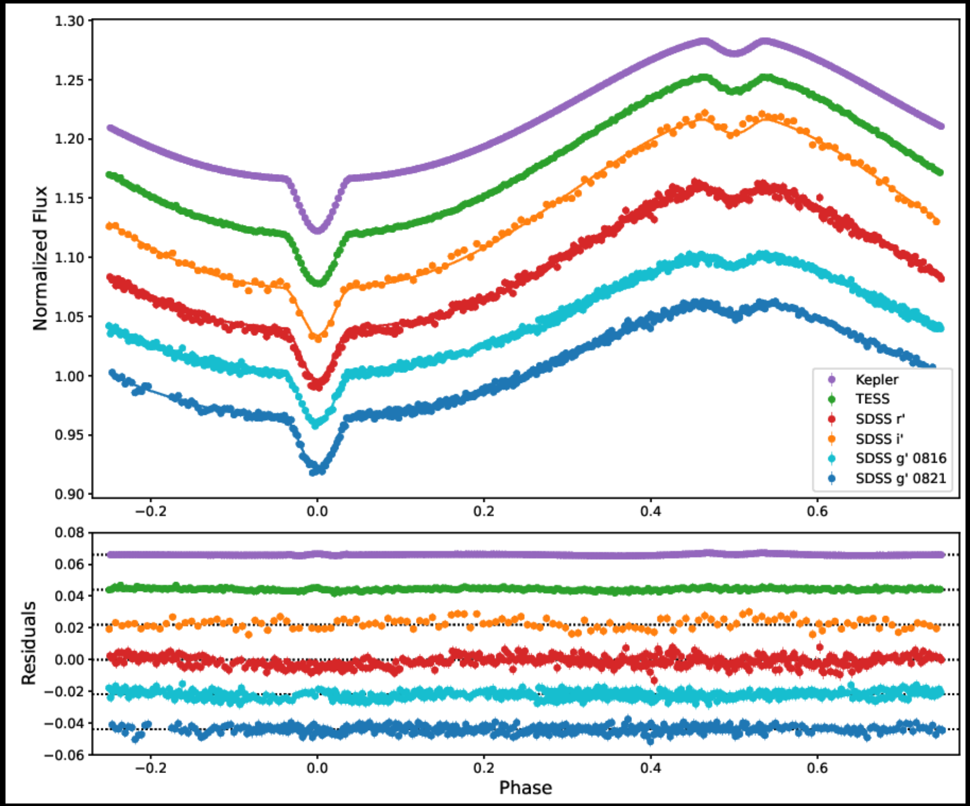
Binary and Multiple Stars in the Era of Big Sky Surveys
Litomysl, 12 September 2024

Binary Star Systems with Evolved Components:

Why are we targeting them to look for sub-stellar objects?

- ✓ The total mass of the components of a Post Common Envelope Binary (PCEB) ($M_1 + M_2 < 1\ M_\odot$) is small, so a planetary mass third body will induce a reflex motion that is observable.
- ✓ Thanks to the comparable sizes of components in a PCEB (WD / sdOB primary & an M dwarf), the light minima are short-lived (~ 15 mins) and hence the minima profiles in their light curves are short-lived making the timing measurements very precise.
- ✓ They have very long baseline of observations to keep track of the variations in their eclipse timings.



Kepler-451 system with an sdB (0.48 $M_\odot$, 0.205 $R_\odot$, 30000 K) and a dM (3000 K, 0.12 $M_\odot$, 0.164 $R_\odot$) with 3 Jovian planets (Esmer, Baştürk, Selam, Aliş 2022)

Binary Star Systems with Evolved Components:
Why are they interesting in terms of planet formation?

- ✓ Planets may form from the matter ejected during the common envelope phase (second generation planets) (Schleicher & Dreizler 2014, Columba+2023, Ledda+2023)
- ✓ Orbital and physical parameters of already existing planets (first generation) might have changed during the binary evolution and the common envelope phase (hybrid scenario) (Ledda+2023)
- ✓ Planets around binaries have better chances to survive later stages of stellar evolution than single stars do (Kostov+2016)
- ✓ These can help us better understand
  - ✓ common envelope phase, which happens very quickly (in thousand year-timescales),
  - ✓ mass-loss mechanisms leading to the formation of hot subdwarf stars,
  - ✓ mixing processes inside the atmospheres of hot subdwarfs,


✓ Planets are always exciting! Orbital architectures, physical characteristics, moons, life ...
Planets around binary stars (circumbinary planets or tattooines) can even be more interesting!

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Astronomy & Astrophysics

Statistics of Magrathea exoplanets beyond the main sequence

Simulating the long-term evolution of circumbinary giant planets with TRES

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The quest for Magrathea planets

I. Formation of second-generation exoplanets around double white dwarfs

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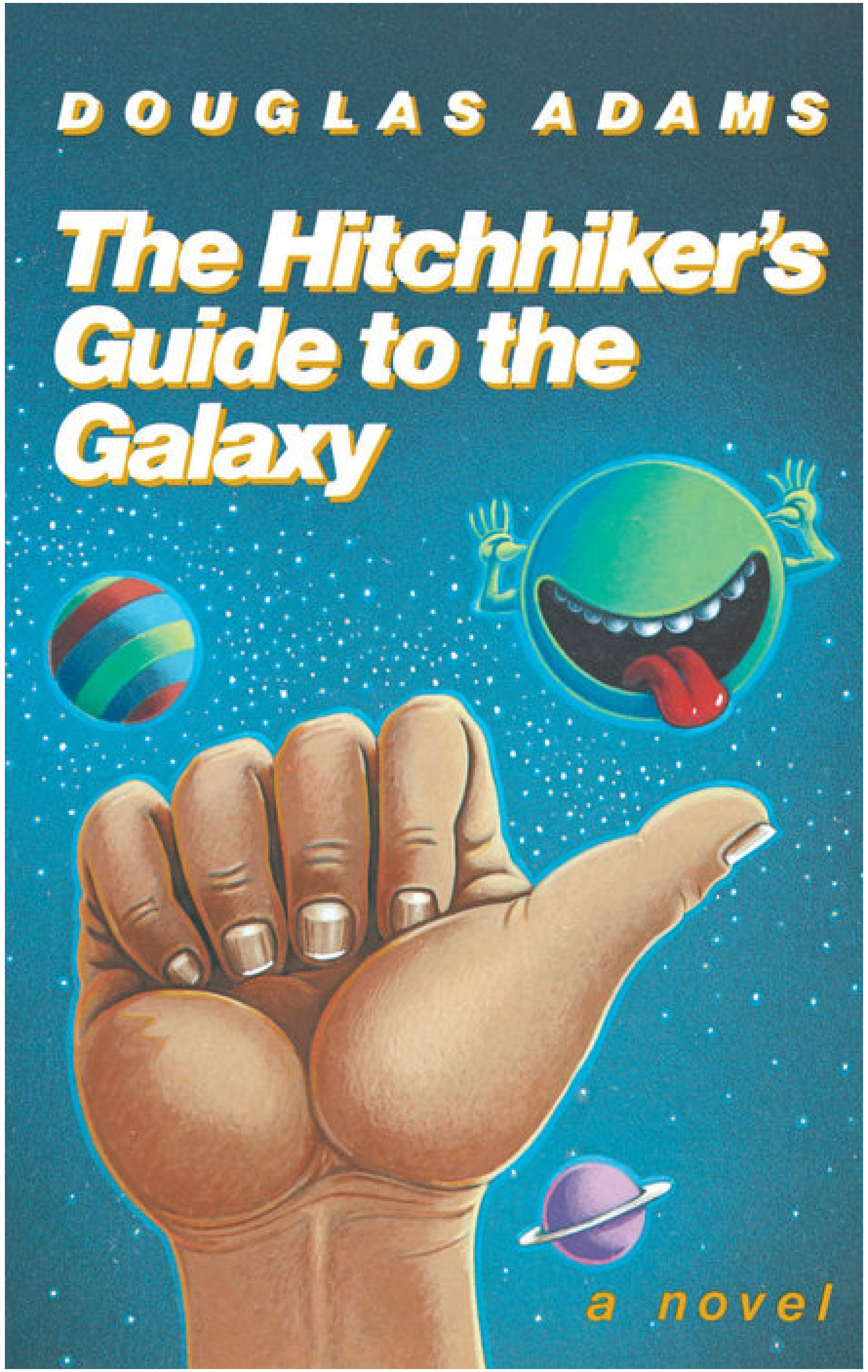
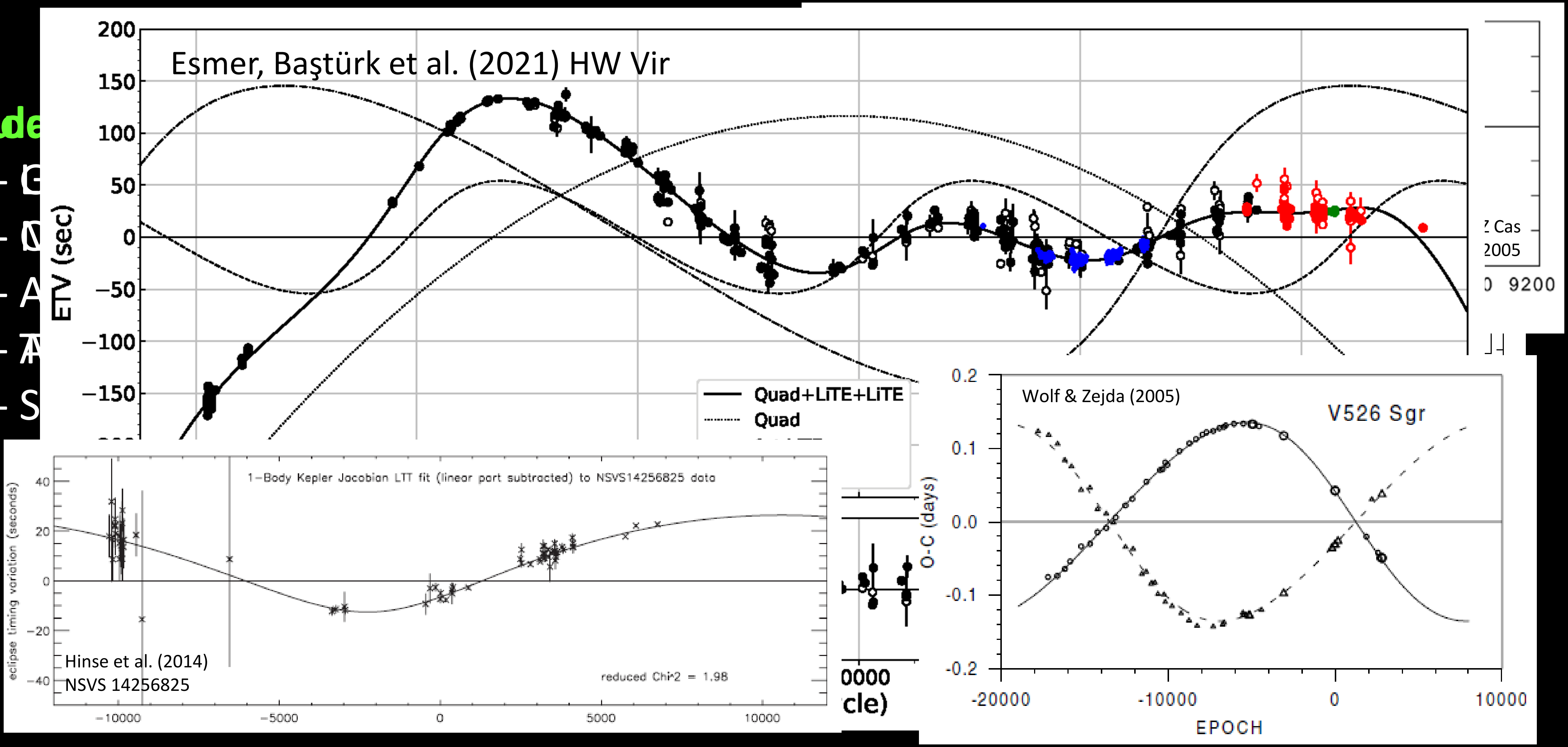
ABSTRACT

Context. The formation of planets around binary stars is the subject of ongoing investigations focusing on the early stages of stellar life. The evolution of binaries that become double white dwarfs (DWDs), however, can cause the ejection of high amounts of dust and gas. This material can give rise to circumbinary discs and become the cradle of new planets, yet no studies to date have focused on the formation of circumbinary planets around DWDs. These binaries will be the main sources of gravitational waves (GWs) detectable by the Laser Interferometer Space Antenna (LISA) mission from the European Space Agency (ESA), opening the possibility to detect circumbinary planets around short-period DWDs everywhere in the Milky Way and in the Large Magellanic Cloud via the modulation of their GW signal.



Eclipse Timing Variations (ETVs)

Changes in the recorded timings of eclipses with respect to a reference orbital period and mid-eclipse timing in a multi-stellar system due to one or combinations of the following reasons



Circumbinary Planets Suggested with ETVs*

Planet	System Type	Reference
HW Vir b	sdB + dM	Lee et al. (2009)
HW Vir c	sdB + dM	Lee et al. (2009)
DE CVn b	WD + WD	Qian et al. (2010)
NN Ser b	WD + dM	Beuermann et al. (2010)
NN Ser c	WD + dM	Beuermann et al. (2010)
DP Leo b	WD + dM	Qian et al. (2011)
HU Aqr b	WD + dM	Qian et al. (2011)
HU Aqr c	WD + dM	Qian et al. (2011)
…	…	…
Kepler-451 b	sdB + dM	Baran et al. (2015)
KIC 5095269 b	G + K	Getley et al. (2017)
KIC 10544976 b	sdB + dM	Almeida et al. (2019)
Kepler-451 c , d	sdB + dM	Esmer et al. (2022)
TOTAL	**23 PCEB planets**	**Out of 24 planets + BD**

* Data from exoplanet.eu and NASA Exoplanet Archive

** 36 planets / BDs have been proposed in 24 systems (6 sdOB + dM, 17 CV, 1 G+K)

Ezgi Sertkan

CuPS-ETV: A Relational Database of Planets Around PCEBs: System

System	T_0	P (days)	a (R_{sol})	a_m	q	q_m	i	d (pc)	Reference
NSVS 14256825	51288.91980	0.110374100	0.85	LC	0.45	assumed	81.9	570	1
NSVS 14256825	54274.20879	0.110374144	NaN	NaN	NaN	NaN	NaN	NaN	2
NSVS 14256825	54274.20882	0.110374065	NaN	NaN	NaN	LC + RV	NaN	NaN	2
…	…	…	…	…	…	…	…	…	…
NN Ser	47344.52400	0.130065000	1.03	LC	NaN	NaN	NaN	NaN	10
NN Ser	47344.52400	0.130065000	0.92	LC	NaN	NaN	NaN	NaN	10
NN Ser	47344.52410	0.130080094	NaN	NaN	NaN	NaN	81	NaN	11
NN Ser	47344.52410	0.130080094	0.95	assumed	0.18	NaN	84	NaN	12
…	…	…	…	…	…	…	…	…	…
KIC 10544976	53590.43613	0.350468722	2.1	RV+LC	NaN	NaN	89.6	590	30
KIC 10544976	53590.08616	0.350468928	0.084	LC	NaN	NaN	89.6	NaN	31
…	…	…	…	…	…	…	…	…	…
OGLE GD-ECL-11388	52743.95069	0.147806480	NaN	NaN	0.289	LC	81.9	NaN	32
OGLE GD-ECL-11388	52743.95067	0.147806181	NaN	NaN	0.289	LC	81.4	NaN	32

CuPS-ETV : Stars

Star	T_{eff} (K)	T_{eff} (method)	log g	log g (method)	Mass ($M_\odot$)	Mass (method)	Radius ($R_\odot$)	Radius (method)	Reference
NSVS 14256825 A	35000	assumed	5.5	LC	0.460	LC	0.2	LC	1
NSVS 14256825 B	3500	assumed	5.35	LC	0.210	LC	0.16	LC	1
...	...	...	...	...	...	...	..	..	...
NN Ser A	NaN	NaN	NaN	NaN	NaN	NaN	0.14	LC	10
NN Ser B	3300	assumed	NaN	NaN	0.280	LC	0.33	LC	10
NN Ser A	45000	spectroscopy	NaN	NaN	0.470	calibration	NaN	NaN	11
NN Ser A	60000	spectroscopy	NaN	NaN	0.600	calibration	NaN	NaN	11
...	...	...	...	...	...	...	..	..	...
Kepler 451 A	10645	LC	3.913	LC	NaN	NaN	79.86	NaN	45
Kepler 451 A	29564	spectroscopy	5.425	spectroscopy	0.480	RV	NaN	NaN	40
Kepler 451 B	NaN	NaN	NaN	NaN	0.120	RV	NaN	NaN	40
Kepler 451 A	NaN	NaN	NaN	NaN	0.372	LC	0.196	estimated	41
Kepler 451 B	NaN	NaN	NaN	NaN	0.100	LC	NaN	NaN	41
...	...	...	...		...	...	..	..	...

CuPS-ETV : Planets

Planet	P (days)	m_2 sini	a (au)	e	w (deg)	T_{per}	M (deg)	Reference
NSVS 14256825 b	7305	12	6.3	0.5	-98	54836	NaN	3
NSVS 14256825 c	1274.7225	2.9	1.9	0	11	55515	NaN	5
NSVS 14256825 d	2505.615	8	2.9	0.52	98	56643	NaN	5
...	...	...	...	...	...	...	..	..
NN Ser b	5661.4	6.91	5.38	0	NaN	NaN	NaN	19
NN Ser c	2830.7	2.28	3.39	0.2	74	NaN	NaN	19
NN Ser b	6110.6	5.92	5.7	0	NaN	NaN	NaN	19
NN Ser c	2443.5225	1.6	3.07	0.13	7	NaN	NaN	19
...	...	...	...	...	...	...	..	..
Kepler 451 b	43	1.76	0.2	0	85	54960	NaN	47
Kepler 451 c	406	1.86	0.9	0.33	302	55131	NaN	47
Kepler 451 d	1460	1.61	2.1	0.29	7	56211	NaN	47
...	...	...	...	...	...	...	..	..

CuPS-ETV : References

System	Author-Year	Reference	ADS link
NSVS 14256825	Wills+2007	1	https://ui.adsabs.harvard.edu/abs/2007IBVS.5800....1W/abstract
NSVS 14256825	Kilkenny+2012	2	https://ui.adsabs.harvard.edu/abs/2012MNRAS.421.3238K/abstract
NSVS 14256825	Beuremann+2012	3	https://www.aanda.org/articles/aa/pdf/2012/04/aa18105-11.pdf
…	…	…	…
NN Ser	Haefner+989	10	https://ui.adsabs.harvard.edu/abs/1989A%26A...213L..15H/abstract
NN Ser	Wood+1991	11	https://ui.adsabs.harvard.edu/abs/1991ApJ...381..551W/abstract
NN Ser	Catalan+1999	12	https://ui.adsabs.harvard.edu/abs/1994MNRAS.269..879C/abstract
NN Ser	Haefner+2000	13	https://ui.adsabs.harvard.edu/abs/2000Msngr.100...42H/abstract
…	…	…	…
OGLE GD-ECL-11388	Hong+2017	32	https://ui.adsabs.harvard.edu/abs/2017PASP..129a4202H/abstract
…	…	…	…
Kepler-451	Esmer+2022	47	https://ui.adsabs.harvard.edu/abs/2022MNRAS.511.5207E/abstract
…	…	…	…

Please see Ezgi Sertkan's Poster Work

EP08: "A catalog of exoplanets around post common envelope eclipsing binaries, CuPS-ETV"

Systems We Follow Currently

System	Type	m_V	Companions
Kepler 451	HS*	12.17	sdB+dM
NY Vir	HS*	13.43	sdB1VIIHe1
HS 2231+2441	HS*	~	sdB+dM
QS Vir	EB*	14.98	DA3+dM
V2051 Oph	CV*	17.5	~
KL UMa	HS*	13.12	sdB
KIC 10544976	WD*	20	DA+M4V
DE CVn	EB*	14.23	DA+M3V
Ton 301	RR*	13.634	~
HS 0705+6700	HS*	~	sdB+dM
DV UMa	CV*	19	DA:+M
DP Leo	CV*	~	~
DD CrB	HS*	~	sdB+dM
UZ For	CV*	~	M4.5

System	Type	m_V	Companions
V588 Vir	HS*	13.64	sdBHe0
NN Ser	CV*	~	DAO1+M4
NSVS 14256825	HS*	12.9	sdOB+dM
HU Aqr	CV*	16.198	D+M4V
SW Sex	CV*	~	~
UU Aqr	CV*	13.998	~
RW Tri	CV*	13.5	M0V
PX And	CV*	15.38	~
DQ Her	CV*	14.605	M3+Ve
V363 Aur	CV*	~	K0V
V1315 Aql	CV*	14.81	~
BT Mon	No*	15.737	G8V
EVR-CB-002	HS*	~	sdB
UCAC2 23234937	HS*	13.73	sdO

* Data from CDS

Systems We Follow Currently (83 in total)

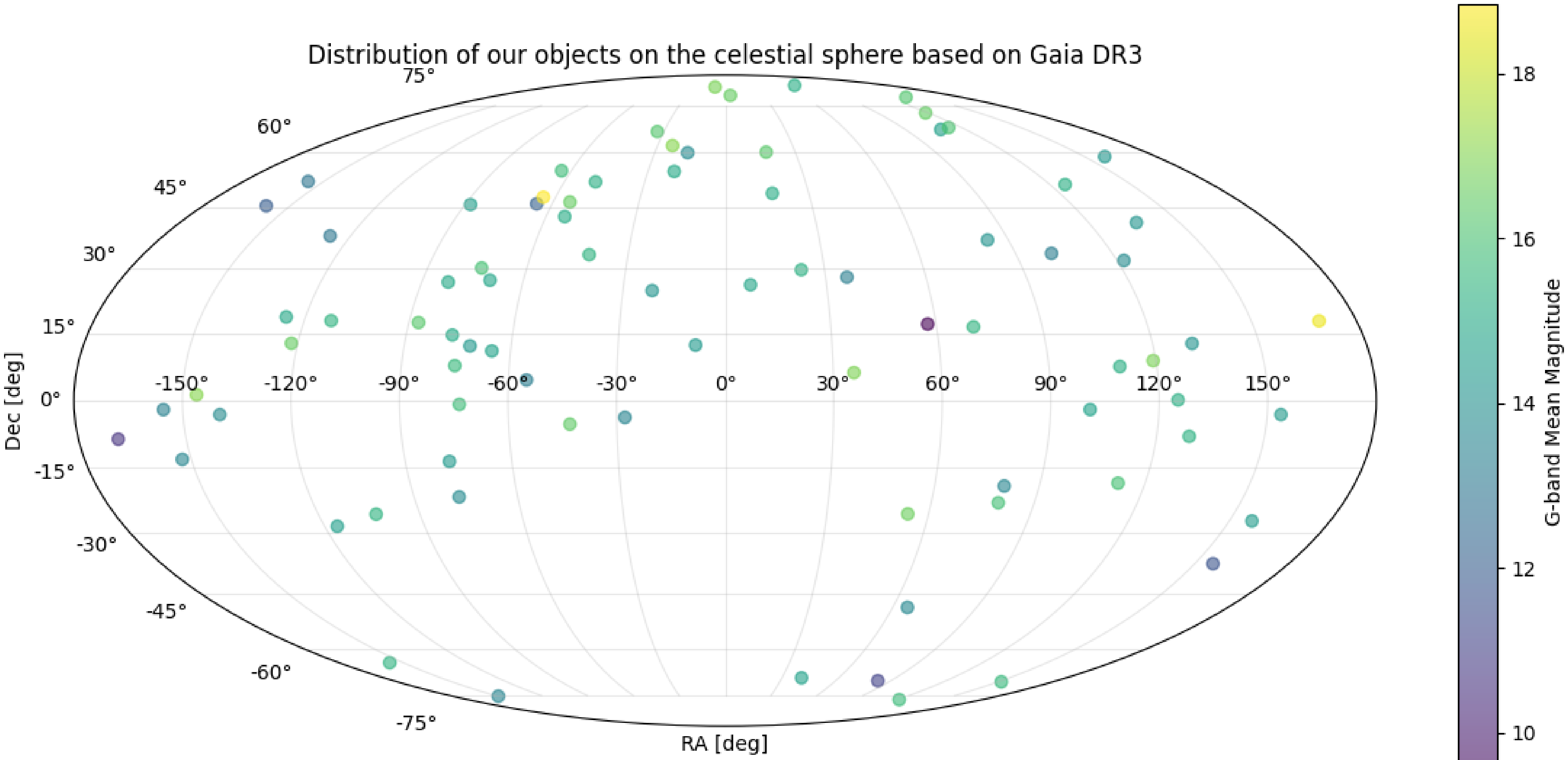
System	Type	m_V	Companions
ATO J294.7689+11.1822	Pu*	~	~
PN A66 46	PN	~	O9k
ATO J340.2132+54.6308	Pu*	~	~
ATO J283.0316+14.7630	EB*	~	~
ATO J306.2869+42.7907	Pu*	15.5	~
GALEX J082053.6+000843	HS*	15.03	sdB
LAMOST J071857.66+073913.2	HS*	~	sdB/sdO
KPD 2045+5136	HS*	15.25	sdB
ATO J129.0542-08.0399	V*	~	~
Gaia DR2 1866796475676061056	HS?	~	~
PG 1628+181	HS*	15.25	sdB
KUV 04390+1631	V*	16.05	B
ATO J284.8528+07.8506	Em*	~	~
ZTF J072905.44-183703.4	EB	15.91	~

System	Type	m_V	Companions
TIC 322390461	HS?	~	~
FBS 0747+725	WD*	16.06	DA:
TIC 609725827	HS?	~	~
Gaia DR2 2287403962995179264	HS?	~	~
Gaia DR3 2202073408192045056	RR*	~	~
UX UMa	CV*	12.78	sdOB
2MASS J22560844+5954299	CV*	15.51	~
ATO J016.9284+48.7552	CV*	15.489	~
ZTF J192014.13+272218.1	EB*	~	~
GALEX J194442.8+544942	HS?	15.8	~
MASTER OT J190519.41+301524.4	CV*	16.5	~
Gaia DR2 4526200711655400064	HS?	~	~
V1776 Cyg	CV*	17.2	~
HE 0516-2311	HS*	15.97	sdB

Systems We Follow Currently (83 in total)

System	Type	m_V	Companions
V482 Cam	CV	16.03	~
TT Tri	CV	15.26	~
V1024 Cep	CV	15.45	~
HS 0220+0603	CV	15.9	~
BP Lyn	CV	14.17	~
PG 0818+513	CV	15.17	~
LX Ser	CV	15.06	~
TIC 240122720	CV	13.56	~
AC Cnc	CV	14.15	~
V471 Tau	V*	9.37	K2V+DA
HT Cas	CV	14.10	~
OGLE GD-ECL-11388	EB	15.71	~
AA Dor	HS*	11.15	sdB+dM
EC 02406–6908	HS*	14.57	sdB

System	Type	m_V	Companions
ASAS J102322-3737.0	HS?	11.51	sdB+dM
GK Vir	WD	17.04	DAe+M
Gaia DR2 4262586854711451904	HS?	~	~
Gaia DR2 2287403962995179264	HS?	~	~
Gaia DR3 2202073408192045056	RR*	~	~
2MASS J07565311+0858319	CV*	~	~
EC 02406-6908	HS*	14.446	sdB
RR Cae	CV	14.40	~
OY Car	CV	15.58	~
EVR-CB-003	HS*	13.53	sdB D
V1776 Cyg	CV	16.54	~
UCAC2 23234937	HS*	13.83	sdO
EVR-CB-002	HS*	13.59	sdB D



Distribution of our objects on the celestial sphere based on Gaia DR3
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
-150°
-120°
-90°
-60°
-30°
0°
30°
60°
90°
120°
150°
Dec [deg]
RA [deg]
G-band Mean Magnitude
18
16
14
12
10

Sources:

- ✓ NASA Exoplanet Archive
- ✓ Extrasolar Planets Encyclopedia
- ✓ Surveys (papers and websites)
- ✓ Announcements in the literature
- ✓ astro.ph

Contrib. Astron. Obs. Skalnaté Pleso **50**, 637 – 641, (2020)
https://doi.org/10.31577/caosp.2020.50.2.637

Possible companions in low-mass eclipsing binaries: V380 Dra, BX Tri, and V642 Vir

M. Wolf[1], H. Kučáková[1,2,3,4], P. Zasche[1], L. Šmelcer[4,5], K. Hornoch[2], K. Hoňková[4], J. Juryšek[4], M. Mašek[4,6] and M. Lehký[4]

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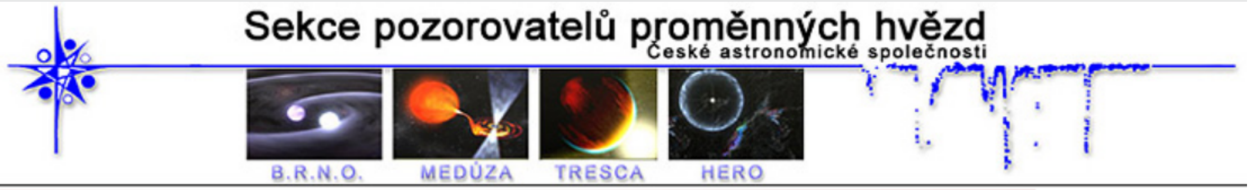
Abstract. We present the new results of our long-term observational project to analyze the orbital period variations of low-mass eclipsing binaries. More then 200 new precise mid-eclipse times recorded with a CCD were obtained for three eclipsing binaries with short orbital periods: V380 Dra ($P = 0\overset{d}{.}49$), BX Tri ($0\overset{d}{.}19$), and V642 Vir ($0\overset{d}{.}52$). Observed-minus-calculated diagrams of the stars were analyzed using all reliable timings, and new parameters of the



O - C gateway
Database of times of minima (E) and maxima (RR)

O-C gateway

Enter **the star's designation**, for which you want to draw an **O-C diagram**. If you're not sure, what's the name of the object in our database, you can choose **search by coordinates** (RA a DE 2000) or **list of all objects** in our database can be shown.

Enter the **star name** [ ] Submit

Search objects **by it's coordinates**

RA 2000: [ ] *HH MM SS*

DE 2000: [ ] *+/-DD MM SS*

field: [10] arcmin Submit

B.R.N.O. database of times of light extrema of periodic variable stars.

Show affiliations

Zejda, M. ; Paschke, A.

A short explanation and motivation on needs, possibilities of establishment and using of a public database of times of minima and maxima of brightness of periodic variables is given.

Publication: 28th Conference on Variable Star Research, p. 115 - 116

Pub Date: 1996

Bibcode: 1996vsr..conf..115Z

Keywords: Data Bases: Variables; Data Bases: Eclipsing Binaries

COMMISSIONS 27 AND 42 OF THE IAU
INFORMATION BULLETIN ON VARIABLE STARS
Number 5583

Konkoly Observatory
Budapest
17 December 2004
HU ISSN 0374 – 0676

CCD TIMES OF MINIMA OF SELECTED ECLIPSING BINARIES

ZEJDA, MILOSLAV

N. Copernicus Observatory and Planetarium, Kraví hora 2, 616 00 Brno, Czech Republic;
e-mail: zejda@hvezdarna.cz

Observatory and telescope:
N. Copernicus Observatory and Planetarium in Brno – 16″ Newtonian telescope (f/1750 mm) (RL400) – 3″ refractor (f/340 mm)(RF80) Vyškov observatory (part of N. Copernicus Observatory and Planetarium in Brno) – 12″ Newtonian telescope (RL300)

Detector:	
	765 × 510+ SBIG ST7 CCD camera (RL400 and RL300) 1530 × 1020+ SBIG ST8 CCD camera (RF80)

Method of data reduction:
Reduction of the CCD frames was made with a software package C-Munipack [1].

Method of minimum determination:
The minima times were computed using several procedures written by A. Gaspani (1995) based on artificial neural networks.

Times of minima:

Star name	Time of min. HJD 2400000+	Error	Type	Filter	Rem.
AB And	52492.4235	0.0010	I	R	MZ; RF80
AB And	52505.5330	0.0011	II	R	MZ; RF80
AB And	52504.5390	0.0012	II	R	MZ; RF80
AB And	52507.5250	0.0013	II	R	MZ; RF80
AB And	52655.3819	0.0013	I	R	MZ; RF80
DO And	52901.6090	0.0032	I	R	MZ; RL400
FK And	51924.3545	0.0069	I	C	MZ; RL400; normal

Observability Program

Menu

Add New	Current Observatory	Min Altitude
	0: ANK	20.0

Day	Month	Year	Hour	Minute	Moon Phase	Min Start Period
12	9	2023	23	0	%4.63	0.9

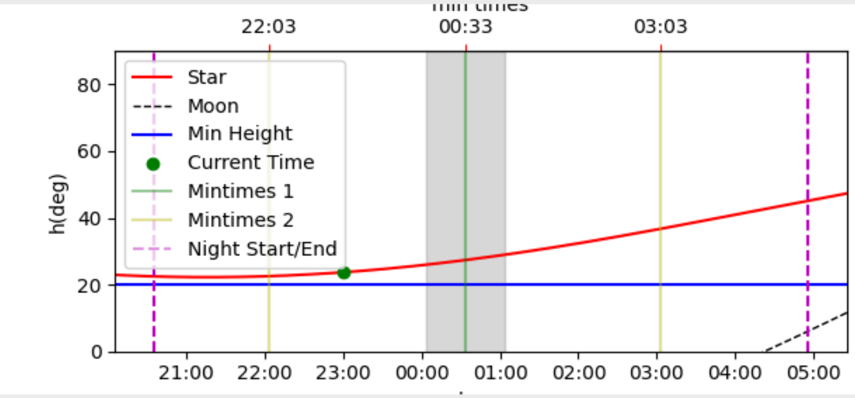
Now | Tonight | Selected Night | Sorting: Default

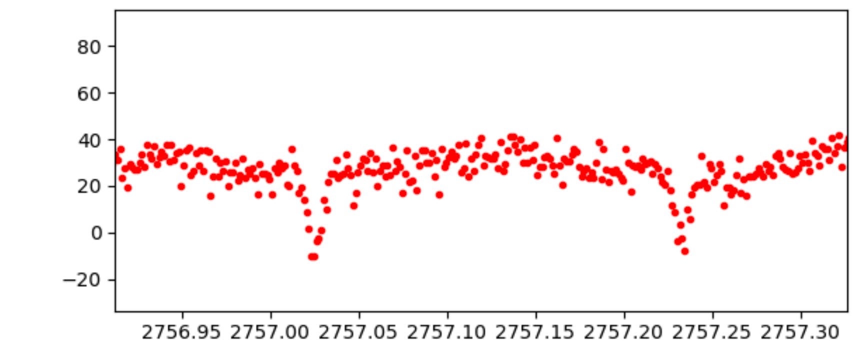
	Star Name	Period	Start	Mintime	End	Mag	Moon Distance
1	GALEX J194442.8+544942	0.0642	23:05	23:14	23:23	15.750846	103
2	HS 0705+6700	0.0956	23:17	23:31	23:44	14.616244	57
3	UU Aqr	0.1636	23:23	23:47	00:10	13.514111	167
4	ATO J294.7689+11.1822	0.2131	23:23	23:54	00:25	14.863745	136
5	V1776 Cyg	0.1647	23:30	23:53	00:17	16.54351	113
6	V1315 Aql	0.1397	23:54	00:14	00:34	14.30002	130
7	FBS 0747+725	0.2083	00:03	00:33	01:03	16.480227	58
8	DQ Her	0.1936	00:05	00:33	01:01	14.589075	98
9	HU Aqr	0.0868	00:09	00:21	00:34	16.434158	163
10	MASTER OT J190519.41+301524.4	0.1297	00:16	00:34	00:53	15.913528	117
11	HS 2231+2441	0.1106	00:32	00:48	01:04	14.169468	137
12	V363 Aur	0.3212	00:39	01:26	02:12	14.115475	61
13	NSVS 14256825	0.1104	00:42	00:58	01:14	13.220149	147
14	2MASS J22560844+5954299	0.2286	01:00	01:33	02:06	14.501919	102
15	ZTF J192014.13+272218.1	0.1494	01:09	01:31	01:52	15.559169	121
16	Kepler 451	0.1258	01:22	01:40	01:59	12.114145	110
17	ATO J340.2132+54.6308	0.2359	01:34	02:08	02:42	14.979544	108
18	PX And	0.1463	01:54	02:15	02:36	14.848258	123
19	Gaia DR2 1866796475676061056	0.2474	02:58	03:33	04:09	15.355584	128
20	ATO J306.2869+42.7907	0.2925	02:59	03:41	04:23	15.065707	117
21	TIC 459182998	0.2344	03:10	03:44	04:18	16.141058	62
22	UZ For	0.0879	03:57	04:10	04:23	16.63771	101
23	NN Ser	0.1301	20:17	20:36	20:55	16.531082	85
24	GALEX J082053.6+000843	0.0962	20:42	20:56	21:09	15.158632	28
25	UX UMa	0.1967	21:08	21:36	22:04	12.930383	55
26	HW Vir	0.1167	21:19	21:36	21:53	10.590079	48

Star Page

Deselect Star

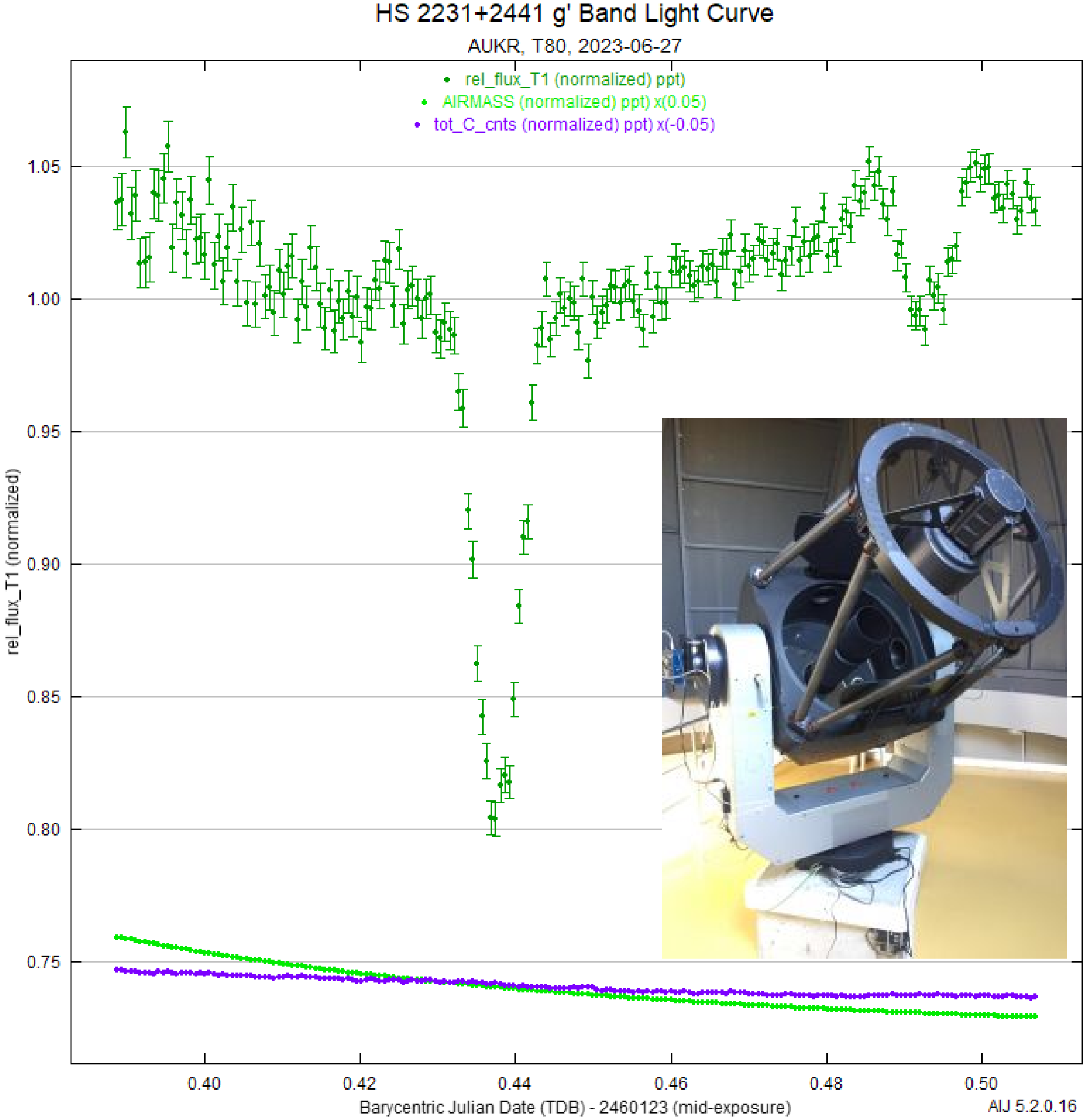
FBS 0747+725 ☑ Legend ☑ Tess Lightcurve

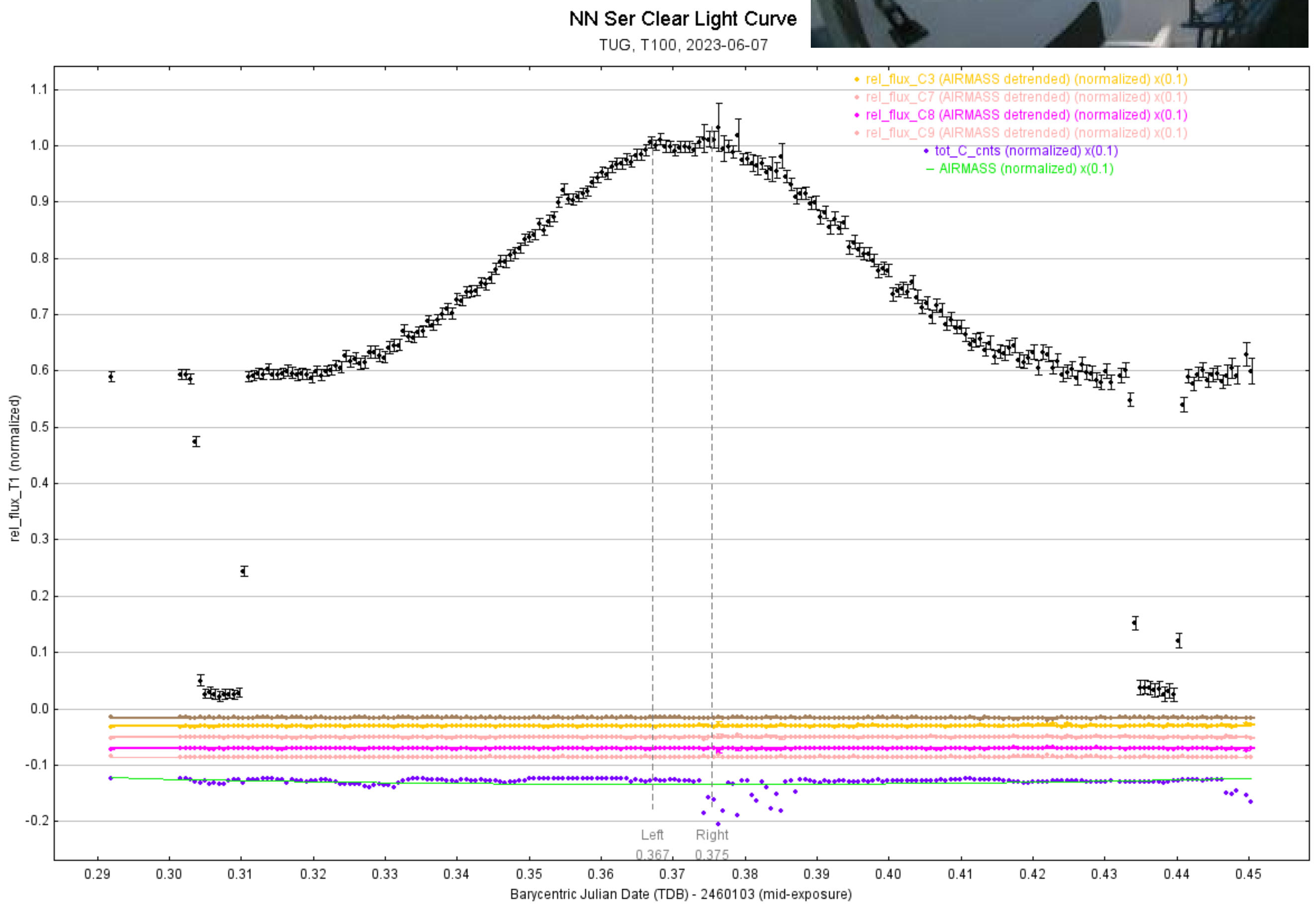




Please see Barış Güler’s poster (GP05) on `ObserPy`

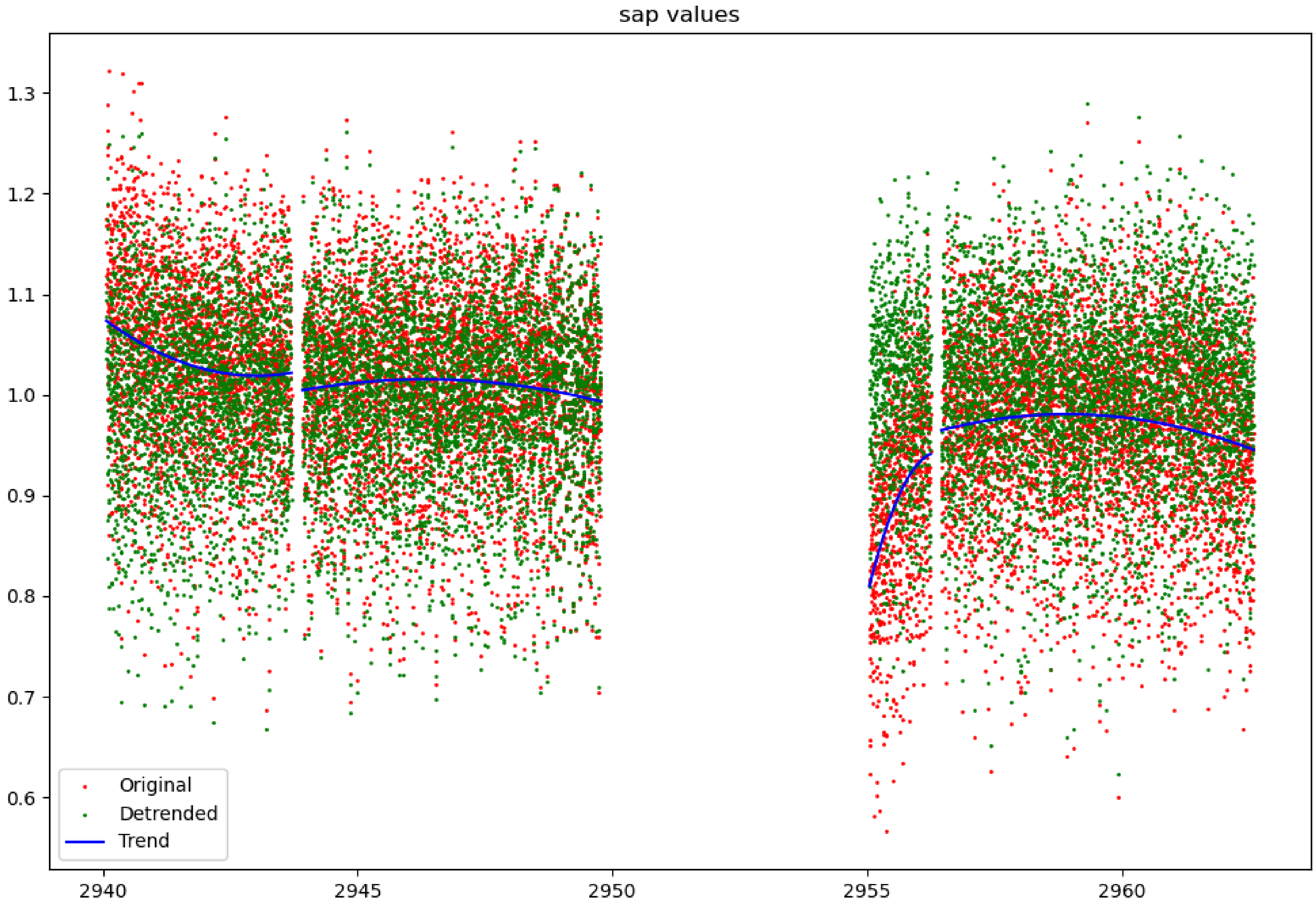
Observations



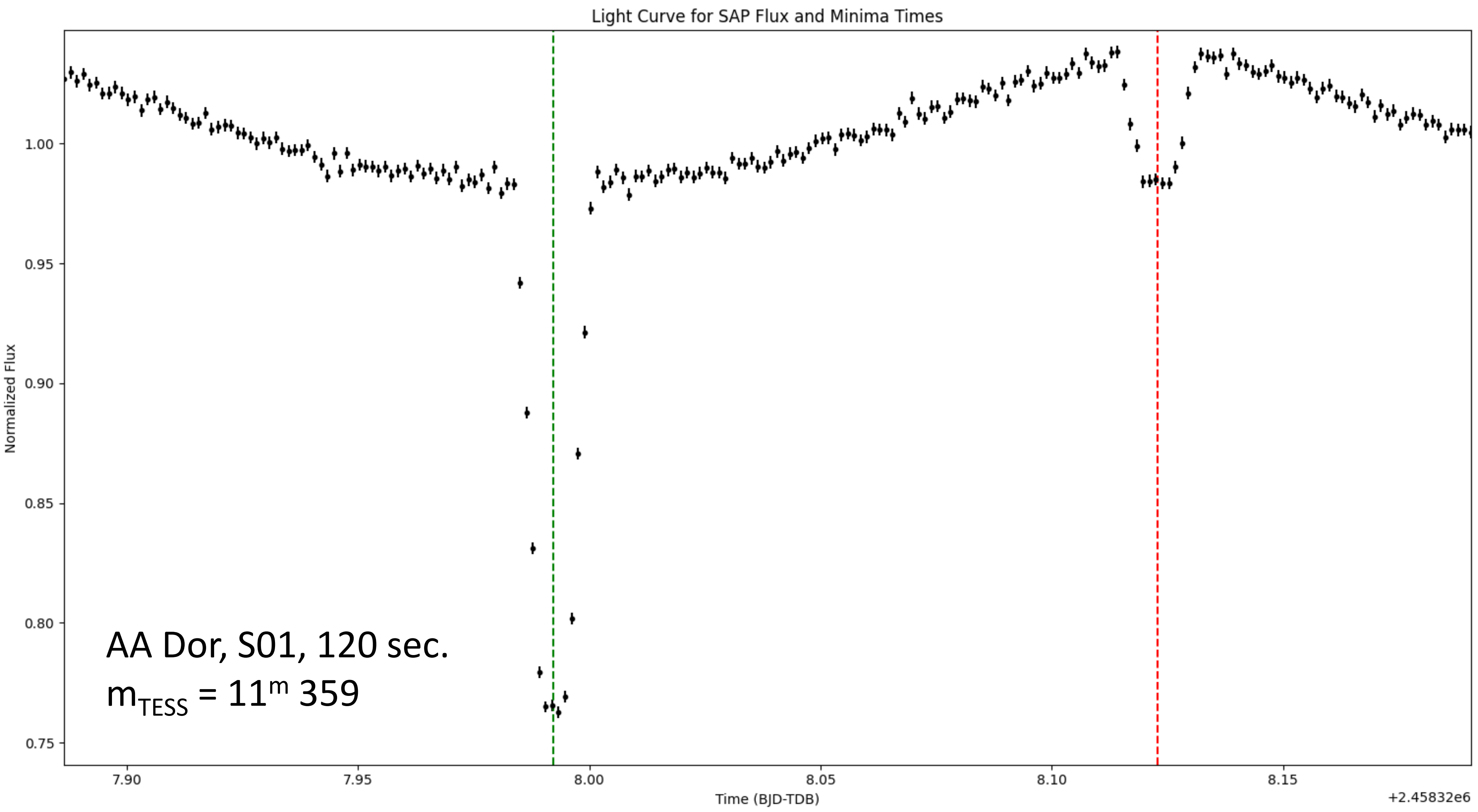


Furkan Akar

Detrending, Normalization, Outlier Removal



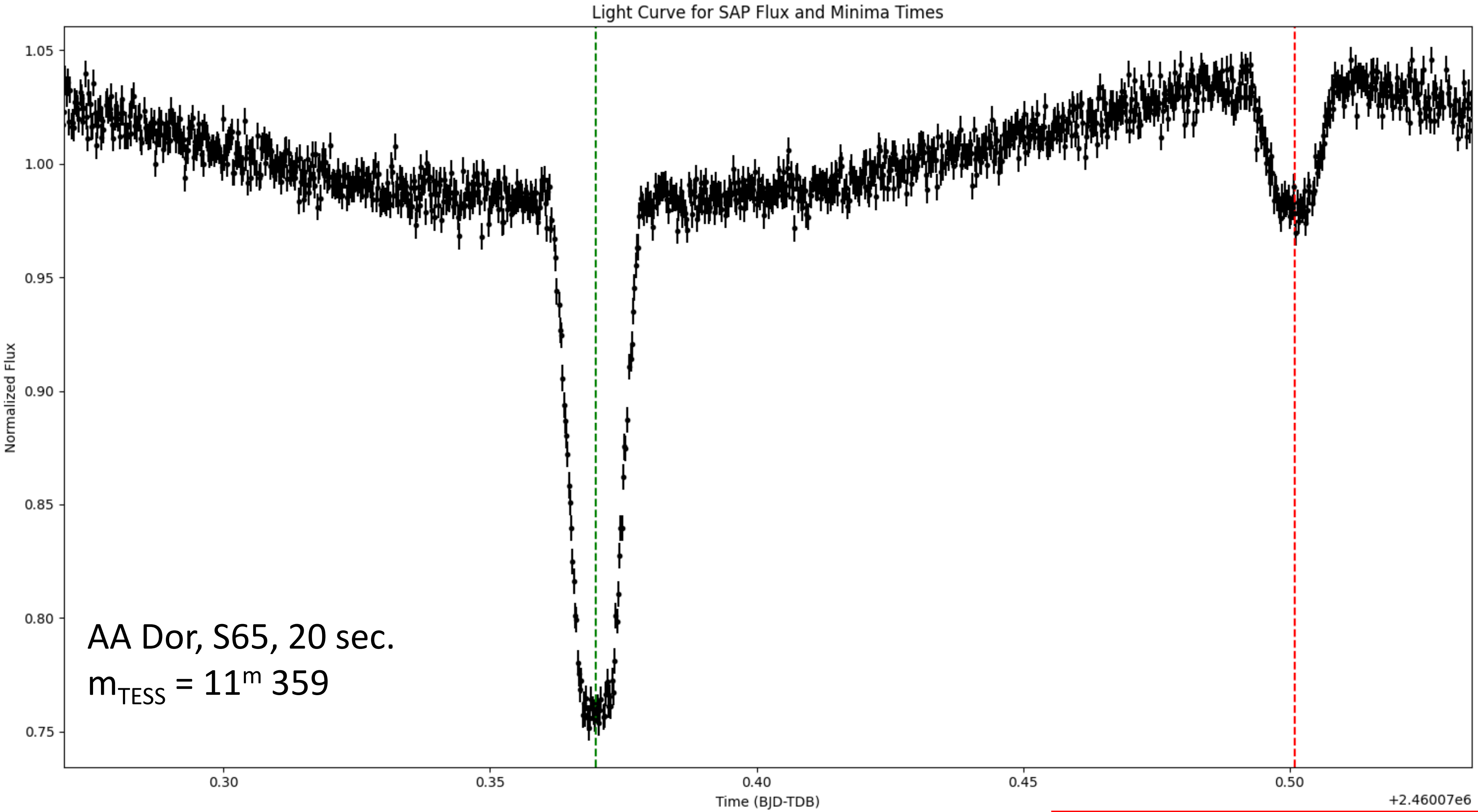
TESS Observations



58334.792272(50) → 4.32 sec.

58334.923044(109) → 9.42 sec.

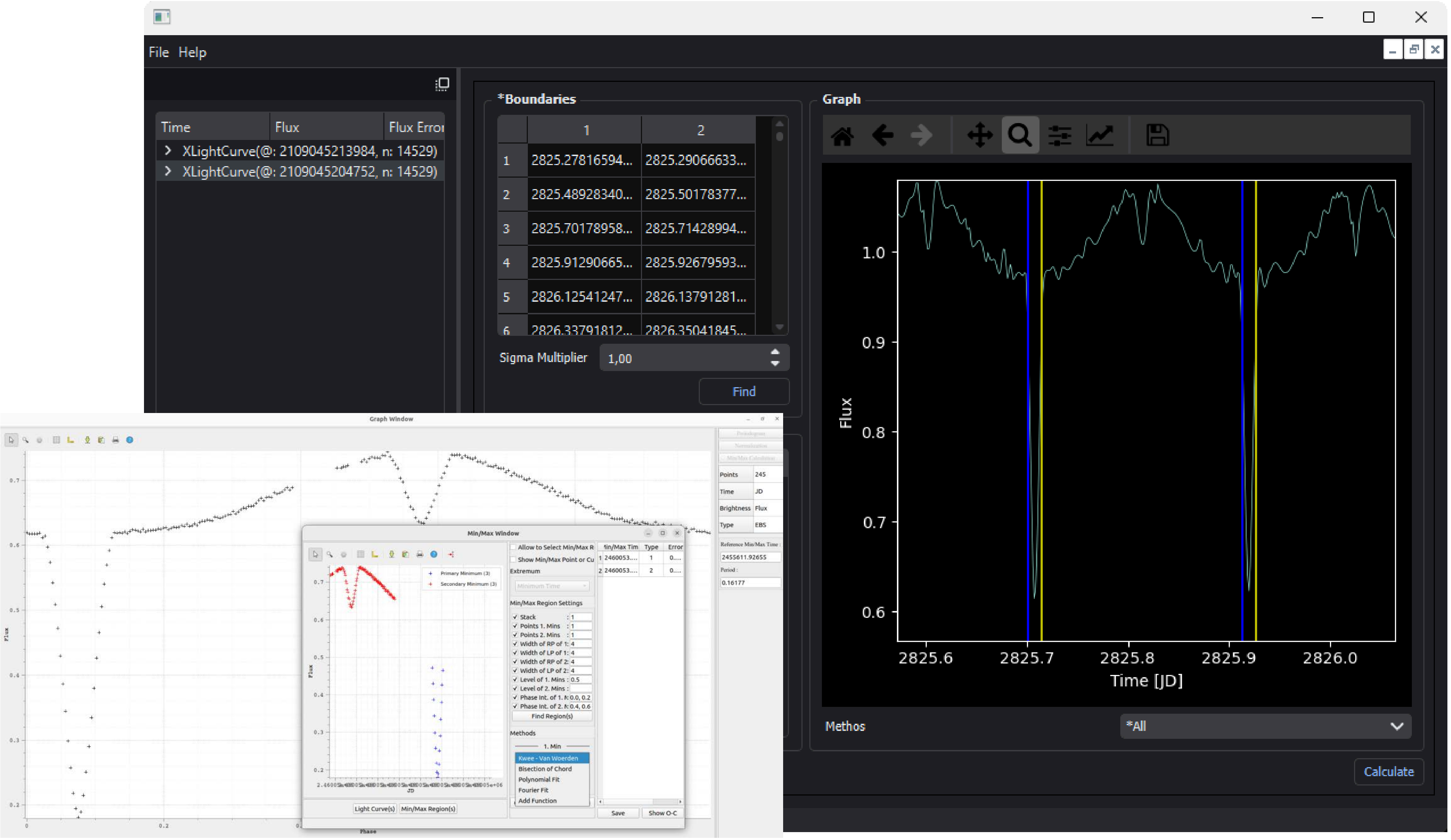
TESS Observations



60076.385406(27) → 2.33 sec.

60076.516335(67) → 5.79 sec.

Measurements of Minima Timings



Xtrema: Bahar et al. (2015)

XLightCurve

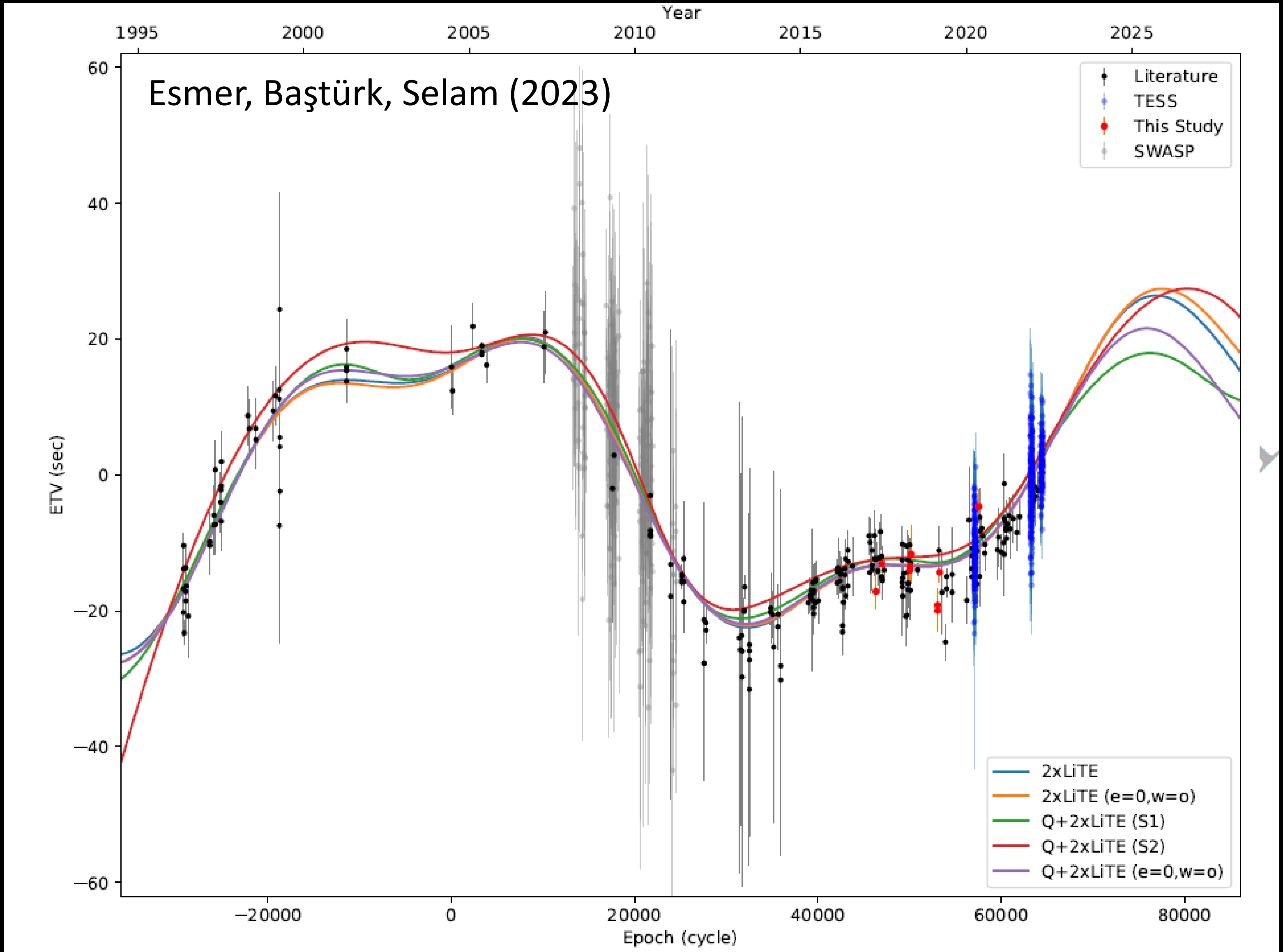
XLightCurve can find minimas using;

- Local,
- Mean or Median,
- Light Curve Fit,
- Kwee - van Woerden (1956),
- Bisector Technique,
- Thoroughgood (2004),
- Periodogram
- Cross Coralation

methods.

Please see FP04 Mohammed Niaei's poster on octans

‘Different Data, Different Solutions, Different Planets?’
NY Vir



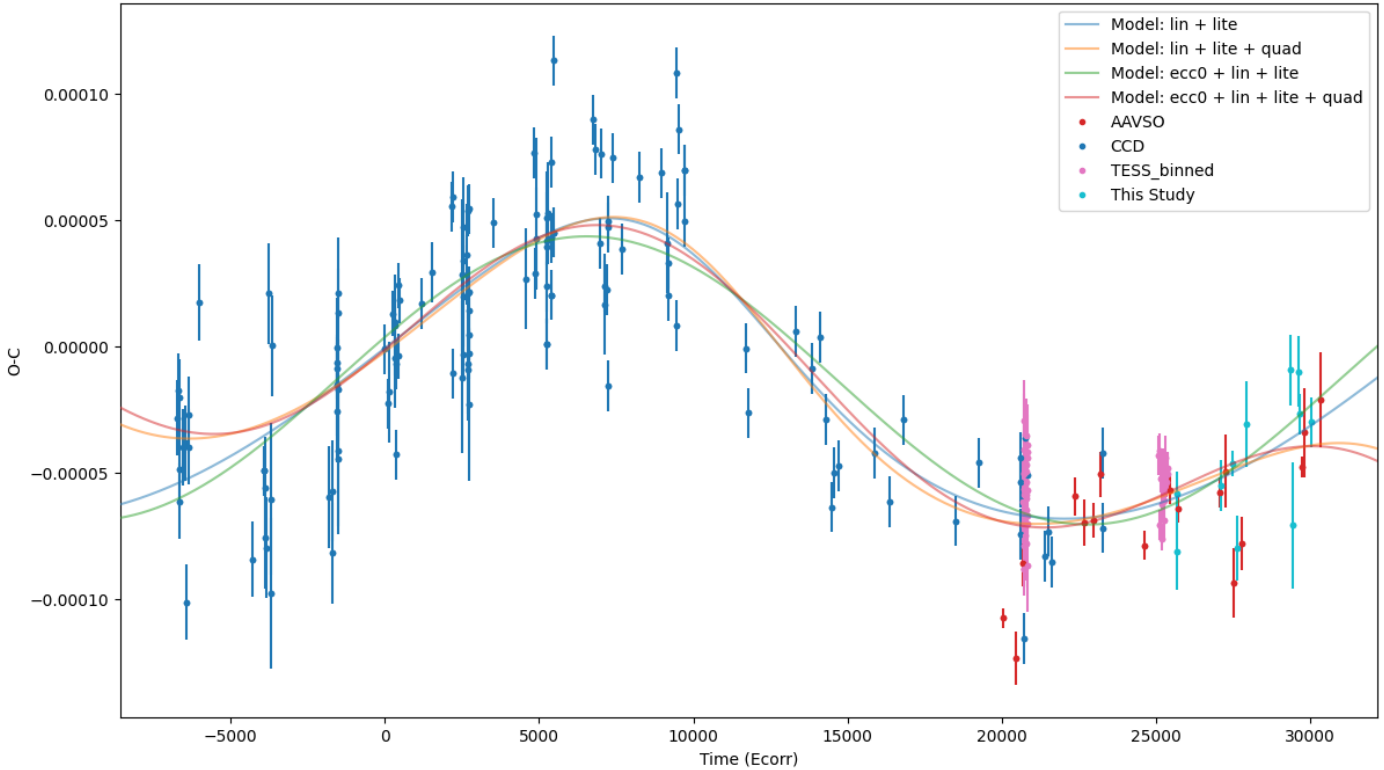
Ekrem M. Esmer (PhD)

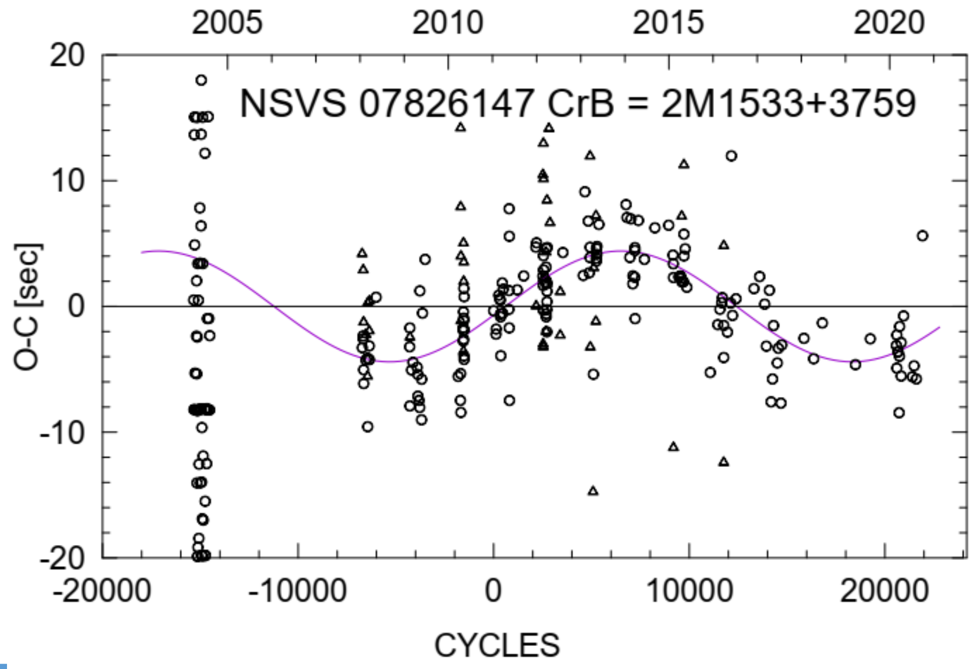
NY Virgo Planets

Parameter	Unit	Qian+2012	Lee+2014	Song+2019	Er+2021	Esmer+2023*
P_3	year	7.9	8.18 ± 0.18	8.64 ± 0.17	8.97 ± 0.36	8.74 ± 0.10
m_3 sini	M_{Jup}	2.3 ± 0.3	2.78 ± 0.19	2.66 ± 0.26	2.74 ± 0.54	2.317 ± 0.102
a_3 sini	AU	3.3	3.39 ± 0.12	3.55 ± 0.01	-	3.579 ± 0.028
e_3	-	0	0.0	0.15 ± 0.08	0.12 ± 0.12	0
ω_3	degrees	-	-	348 ± 6	351 ± 69	-
P_4	year	-	27.0 ± 3.7	24.09 ± 0.65	27.2 ± 1.3	23.01 ± 1.12
m_4 sini	M_{Jup}	-	4.49 ± 0.72	5.54 ± 0.20	5.59 ± 0.51	3.996 ± 0.166
a_4 sini	AU	-	7.54 ± 0.64	7.04 ± 0.25	-	6.83 ± 0.22
e_4	-	-	0.44 ± 0.17	0.15 ± 0.01	0.19 ± 0.09	0.033 ± 0.023
ω_4	degrees	-	333 ± 15	320 ± 4	398 ± 42	28 ± 9
dP / dE	10^{-12} d / cyc	-4.6 ± 0.4	-	-	-5.28 ± 0.48	-

* Esmer, Baştürk, Selam, MNRAS, 525, 6050

DD CrB O-C Diagram (Preliminary Results)

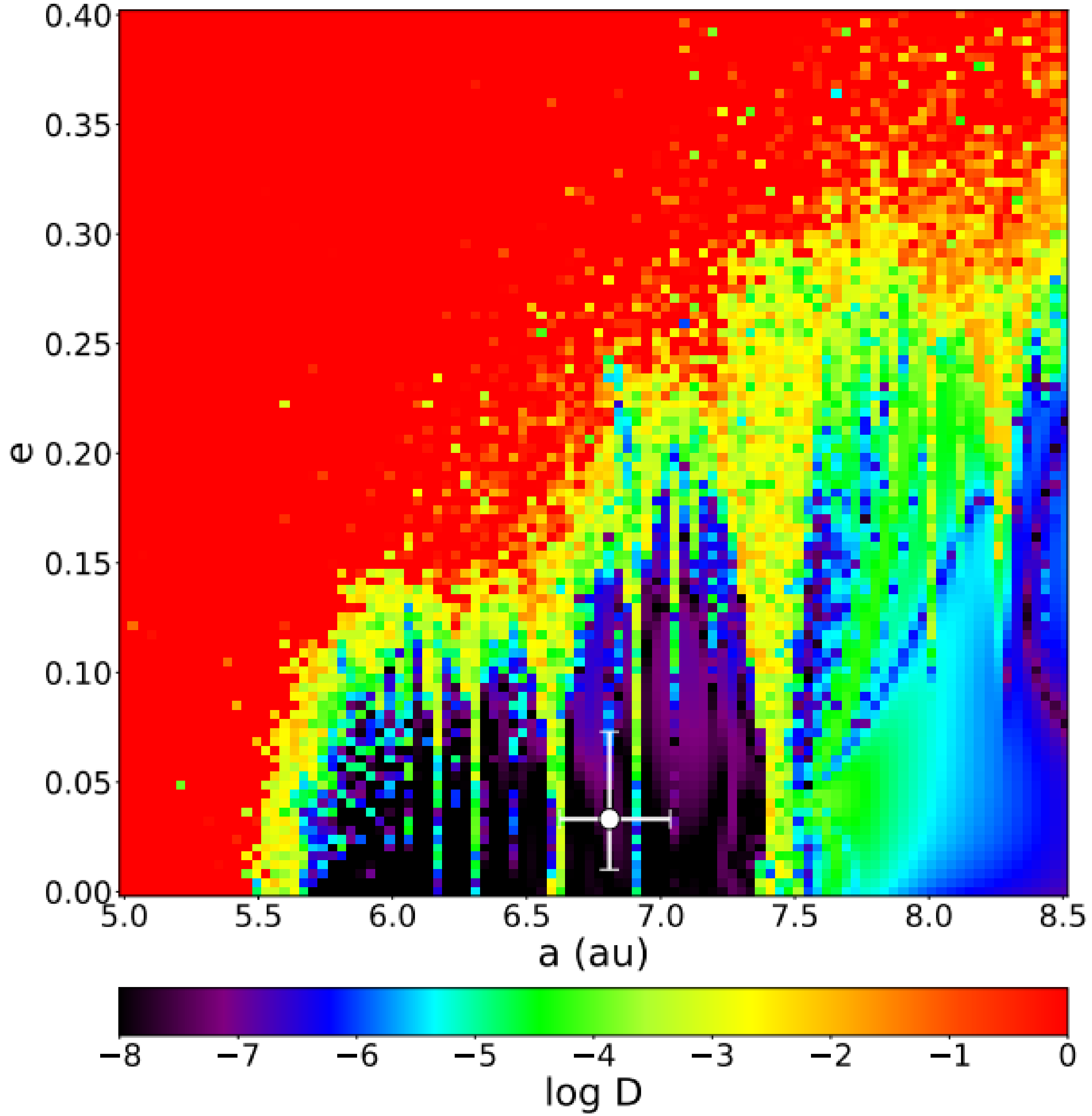




	lin + lite	lin + lite + quad	ecc0 + lin + lite	ecc0 + lin + lite + quad
dP (day)	-2.55e-11 ± 4.94e-11	2.64e-11 ± 4.91e-11	-4.84e-11 ± 4.93e-11	3.40e-11 ± 4.88e-11
dT (day)	-8.30e-06 ± 1.27e-06	1.19e-05 ± 1.91e-06	-1.27e-05 ± 1.05e-06	1.05e-05 ± 1.58e-06
ecc	0.28 ± 0.03	0.18 ± 0.04	0 (fixed)	0 (fixed)
omega (deg)	129.62 ± 6.20	140.73 ± 11.47	-8.36 ± 5.90	78.29 ± 19.12
P_{LiTE} (yrs)	14.75 ± 1.25	11.08 ± 1.86	14.33 ± 0.91	11.06 ± 1.33
T_{LiTE}	2462597 ± 799	2461399 ± 935	2460480 ± 493	2460709 ± 1386
A (sec)	5.12 ± 0.09	3.86 ± 0.12	4.90 ± 0.09	3.65 ± 0.09
Q		-9.38e-14 ± 8.73e-15		-9.58e-14 ± 6.55e-15
M_3 (M_J)	1.32 ± 0.04	1.20 ± 0.03	1.27 ± 0.03	1.12 ± 0.03
a_3 (AU)	5.11 ± 0.20	4.22 ± 0.19	5.01 ± 0.19	4.22 ± 0.18
χ^2_υ	5.36	5.33	5.86	5.47
AIC & BIC	1108 & 1131	1097 & 1123	1212 & 1232	1129 & 1152

Element	Unit	S1435	N782
T_0	BJD-2400000	54148.70395(2)	55611.92657(3)
P_s	days	0.125630981(5)	0.161770446(2)
P_3	days	4765(85)	3820(140)
P_3	years	13.0(0.3)	10.5(0.4)
e_3	–	0.05(4)	0.0
A	days	0.00063(2)	0.000050(3)
A	sec	54.4(1.7)	4.3(0.3)
ω_3	deg	23.7(3.0)	204.1(2.5)
T_3	JD-2400000	54930(20)	50155(20)
$a_{12} \sin i$	au	0.109	0.0087
$\sum w\,(O–C)^2$	day^2	3.4×10^{-7}	1.4×10^{-7}

Wolf et al. (2021)



Esmer, Baştürk, Selam (2023)

Magnetic Activity Assumption

System*	P_{ETV} (yrs)	A_{ETV} (sec)	$\Delta E / E_{sec}$ *	$A_{qmc, 5 yrs}$	$A_{qmc, 10 yrs}$	$A_{qmc, 20 yrs}$	A_{q5} / A_{ETV}	A_{q10} / A_{ETV}	A_{q20} / A_{ETV}
DP Leo	28.80	66.7	1.40	4.09	11.56	32.69	0.06	0.17	0.49
KIC 10544976	16.80	80.1	70.50	1.67	4.72	13.32	0.02	0.06	0.17
OGLE-ECL-11388	8.90	634.3							
OY Car	14.00	65.4							
RR Cae	11.90	33.9	447.20	4.30	1.53	0.54	0.13	0.05	0.02
SW Sex	36.57	1400.2							
V2051 Oph	21.64	62.2							
DE CVn	11.22	66.9							
QS Vir	7.86	21.1	0.79	12.22	34.53	97.54	0.58	1.64	4.62
V893 Sco	10.19	43.7							
DV UMa	17.58	149.5							
DD CrB b	10.46	9.0	8.01	1.06	3.00	8.48	0.12	0.33	0.94
SDSS J1435+3733	10.46	9.0							
GK Vir	13.05	109							

* Based on best LiTE solutions of the ETVs from the literature

** Assuming two-zone model by Völschow et al. (2016)

Magnetic Activity Assumption: Multi-planet Systems

System*	P_{ETV} (yrs)	A_{ETV} (sec)	$\Delta E / E_{sec}$ *	$A_{qmc, 5\ yrs}$	$A_{qmc, 10\ yrs}$	$A_{qmc, 20\ yrs}$	A_{q5} / A_{ETV}	A_{q10} / A_{ETV}	A_{q20} / A_{ETV}
HW Vir	28.21	317	26.55	4.85	13.71	38.67	0.02	0.04	0.12
Kepler-451	4.93	8.9	19.85	2.06	5.83	16.45	0.23	0.65	1.85
NN Ser	16.05	67.4	85.19	1.33	3.76	10.62	0.02	0.06	0.16
NSVS 14256825	7.00	50.2	109.39	2.96	8.39	23.69	0.06	0.17	0.47
NY Vir	27.00	56.8	2.45	2.91	8.21	23.30	0.05	0.14	0.41
UZ For	14.75	73.5	10.67	4.48	12.65	35.76	0.06	0.17	0.49
V470 Cam	14.48	171	43.31	5.40	15.20	42.99	0.03	0.09	0.25
HU Aqr	19.61	181	4.23	11.41	35.25	91.11	0.06	0.18	0.50

* Based on best LiTE solutions of the ETVs from the literature

** Assuming two-zone model by Völschow et al. (2016)

Verification of LiTE Signals with Independent Methods

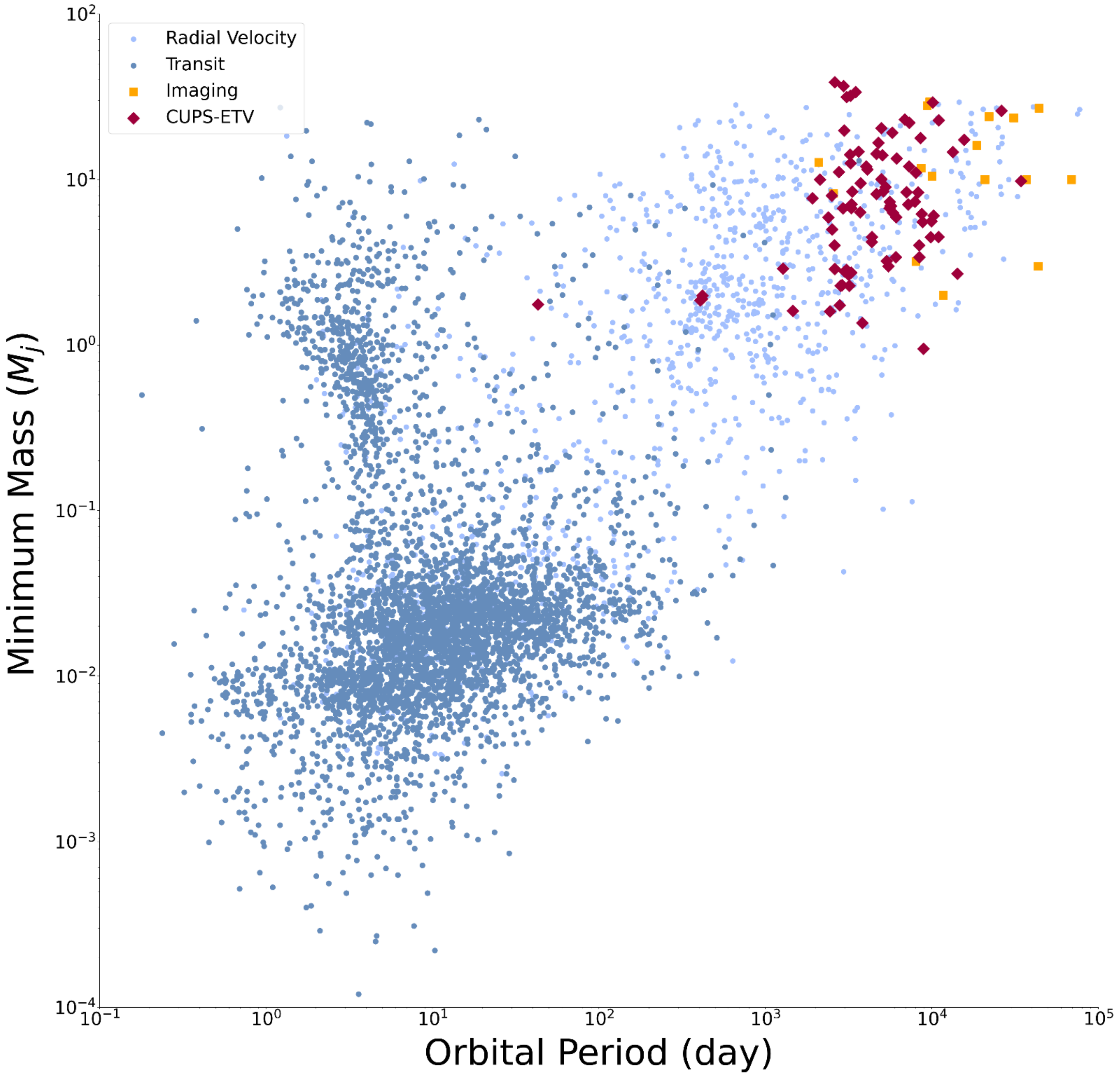
System*	P_{ETV} (yrs)	A_{ETV} (sec)	A_{RV} (m/s)	$A_{Imaging}$ (mas)	p_{tr} (ecc.) (%)	p_{tr} (circ.) (%)**
DP Leo	28.80	66.7	155.4	47.29	0.0005	0.0007
KIC 10544976 b	16.80	80.1	308.9	24.78	0.0009	0.0010
OGLE-ECL-11388 b	8.90	634.3	4254.4	4.01		
OY Car b	14.00	65.4	222.1	135.00		0.0008
RR Cae b	11.90	33.9	131.1	497.13		0.0014
SW Sex b	36.57	1400.2	2509.9	29.36		0.0007
V2051 Oph b	21.64	62.2	153.9	8.94	0.0006	0.0005
DE CVn b	11.22	66.9	281.1	372.49		0.0011
QS Vir b	7.86	21.1	177.8	161.97	0.0017	0.0012
V893 Sco b	10.19	43.7	283.1	72.08		
DV UMa b	17.58	149.5	492.6	42.81	0.0006	0.0004
DD CrB b	10.46	9.0	51.6	15.05		0.0010
SDSS J1435+3733 b	13.05	109	500.0	53.01		
GK Vir b	24.34	9.7	24.3	29.87	0.0010	0.0011

* Based on best LiTE solutions of the ETVs from the literature

** Assuming Mass-Radius relation for planets from Chen & Kipping (2013)

Verification: Multi-planet Systems

System	P_{ETV} (yrs)	A_{ETV} (sec)	A_{RV} (m/s)	$A_{Imaging}$ (mas)	p_{tr} (ecc.) (%)	p_{tr} (circ.) (%)**
HW Vir	28.21	317	1398.7	88.18	0.0128, 0.0204	0.0103 0.0178
Kepler-451	4.93	8.9	512.8	11.75 (c)	0.0856 0.0513 0.4767	0.1059 0.0454 0.4767
NN Ser	16.05	67.4	305.6	21.27	0.0019 0.0024	0.0018 0.0029
NSVS 14256825	7.00	50.2	534.8	7.85	0.0626 0.0460	0.0301 0.0460
NY Vir	27.00	56.8	238.2	24.20	0.0206 0.0092	0.0206 0.0093
UZ For	14.75	73.5	367.6	47.14	0.0028 0.0020	0.0009 0.0017
V470 Cam	14.48	171	1672.2	7.98	0.0327 0.0227	0.0327 0.0227
HU Aqr	19.61	181	857.4	77.40	0.0009 0.0006	0.0007 0.0006

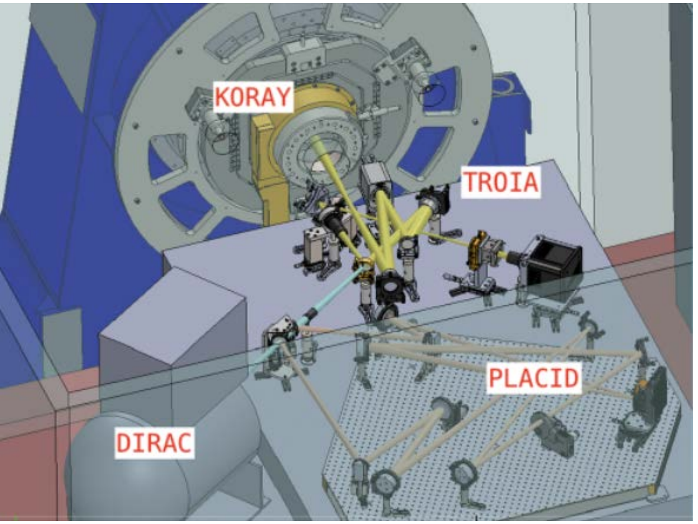


Data Source: NASA Exoplanet Archive & CUPS-ETV

Ezgi Sertkan's poster

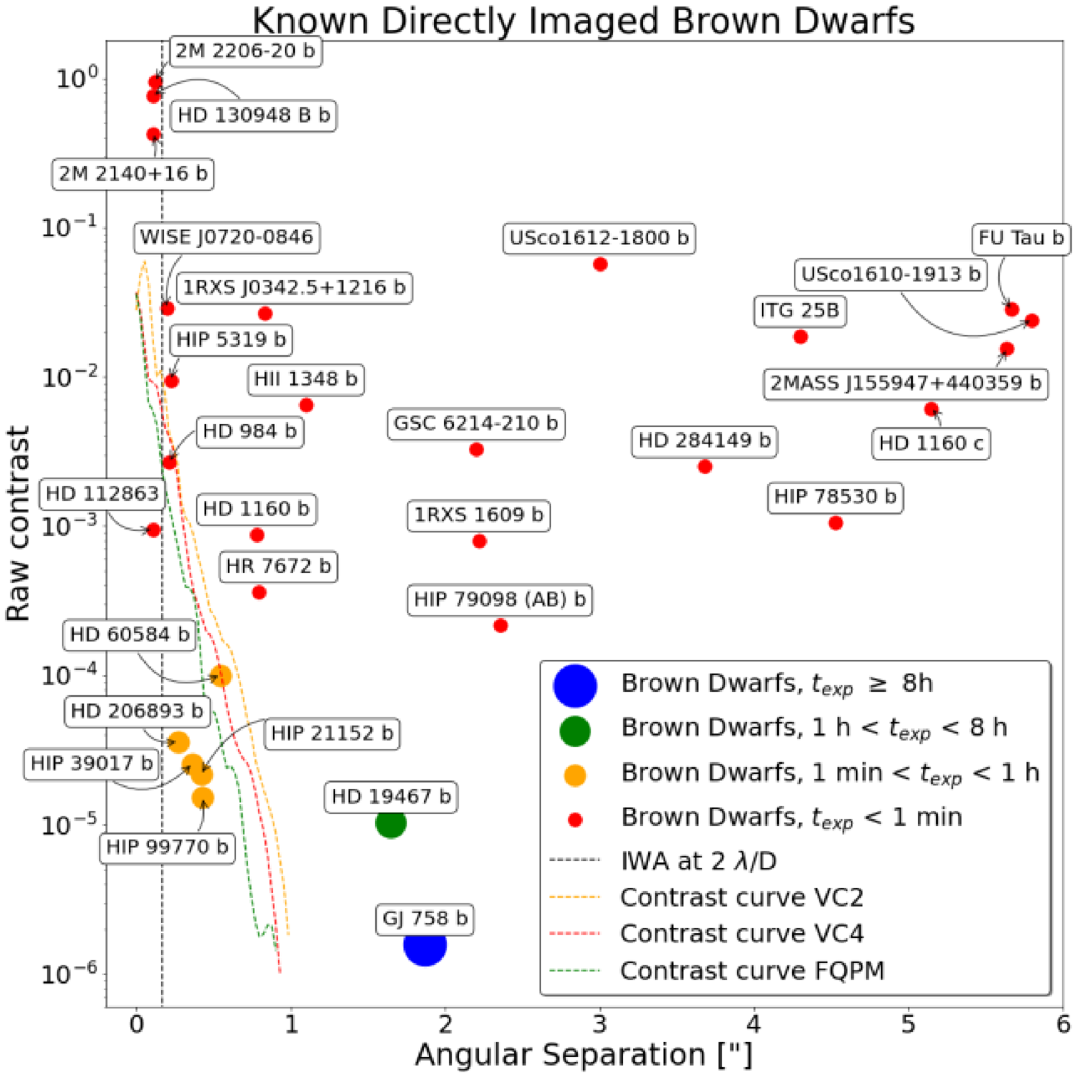
East Anatolian Observatory (DAG)
4 meter Telescope and the Direct Imaging System (DGS)

Name	Doğu Anadolu Gözlemevi (DAG)
Location	Karakaya Ridge, Erzurum, Turkey
Latitude	39°46'50.0" N
Longitude	41°13'36.0" E
Altitude	3170 m
Seeing (lowest, median)	0.3" - 0.9"
Primary mirror	4 m
Focal length	56 m
Mounting	Altitude - Azimuth
Telescope build	Ritchey - Chrétien
Declination limit	≥ -24°



Name	PLACID
Observing bands	H-band: 1.63 μm (Ks-band: 2.15 μm)
SLM specification	1920 x 1152 px, 8 bits
FoV	16" x 9.6"
λ/D at H-band	85 mas
Optical throughput	> 22%

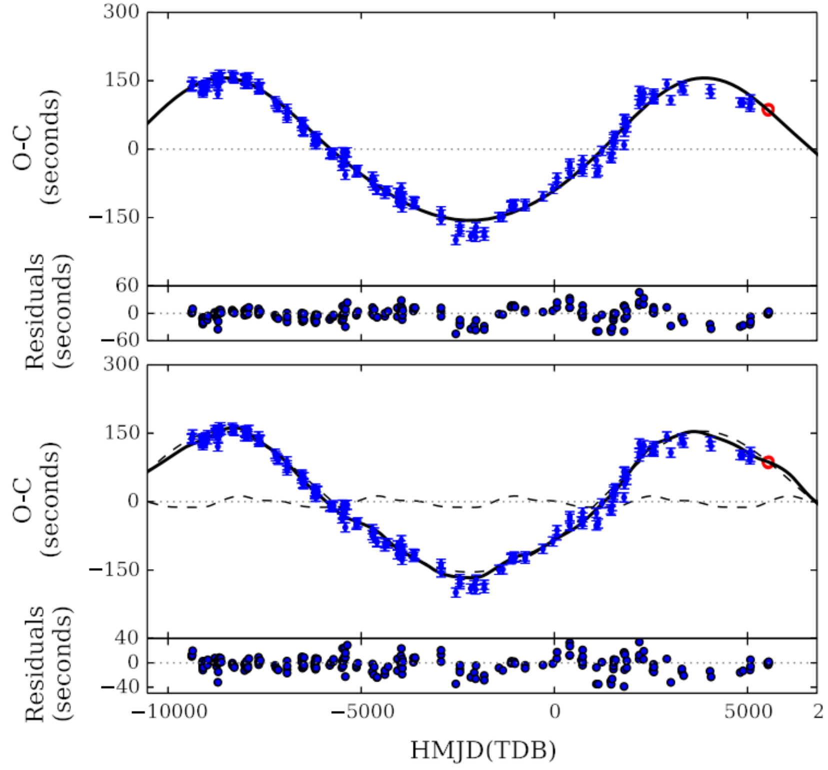
Name	DIRAC
Detector	Teledyne H1RG, 1024 x 1024 px
Wavelength range	900 - 2400 nm
Fill factor	100%
Minimum exposure time	~ 1 s
Read-out noise	~ 18 e$^-$
Read-out gain	1.8 e$^-$/ADU

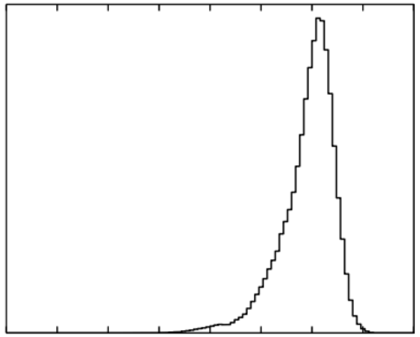


The system is expected to be operational in 2025. Please see Fatma Tezcan's poster (GP23) on DAG!

Tandon et al. 2024

Can we actually see these substellar companions?





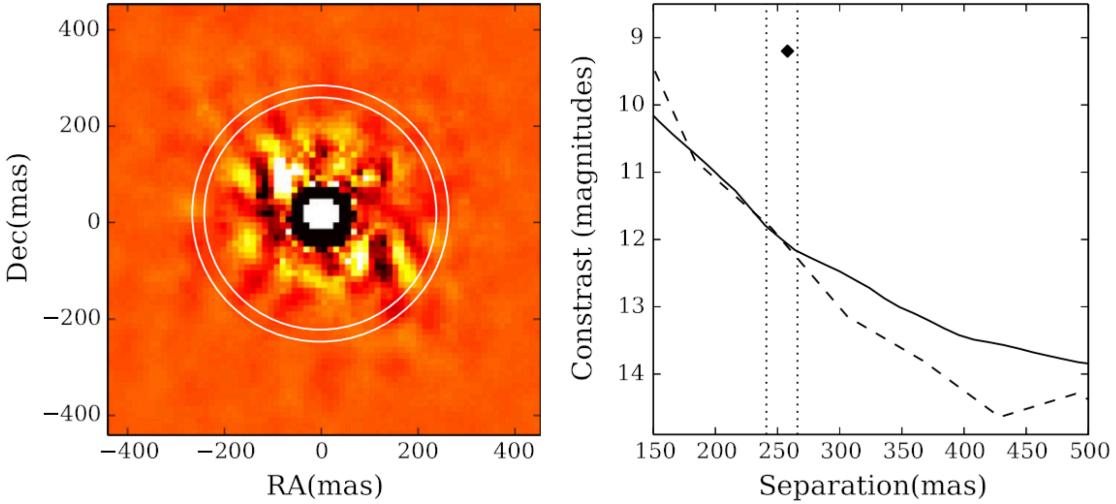


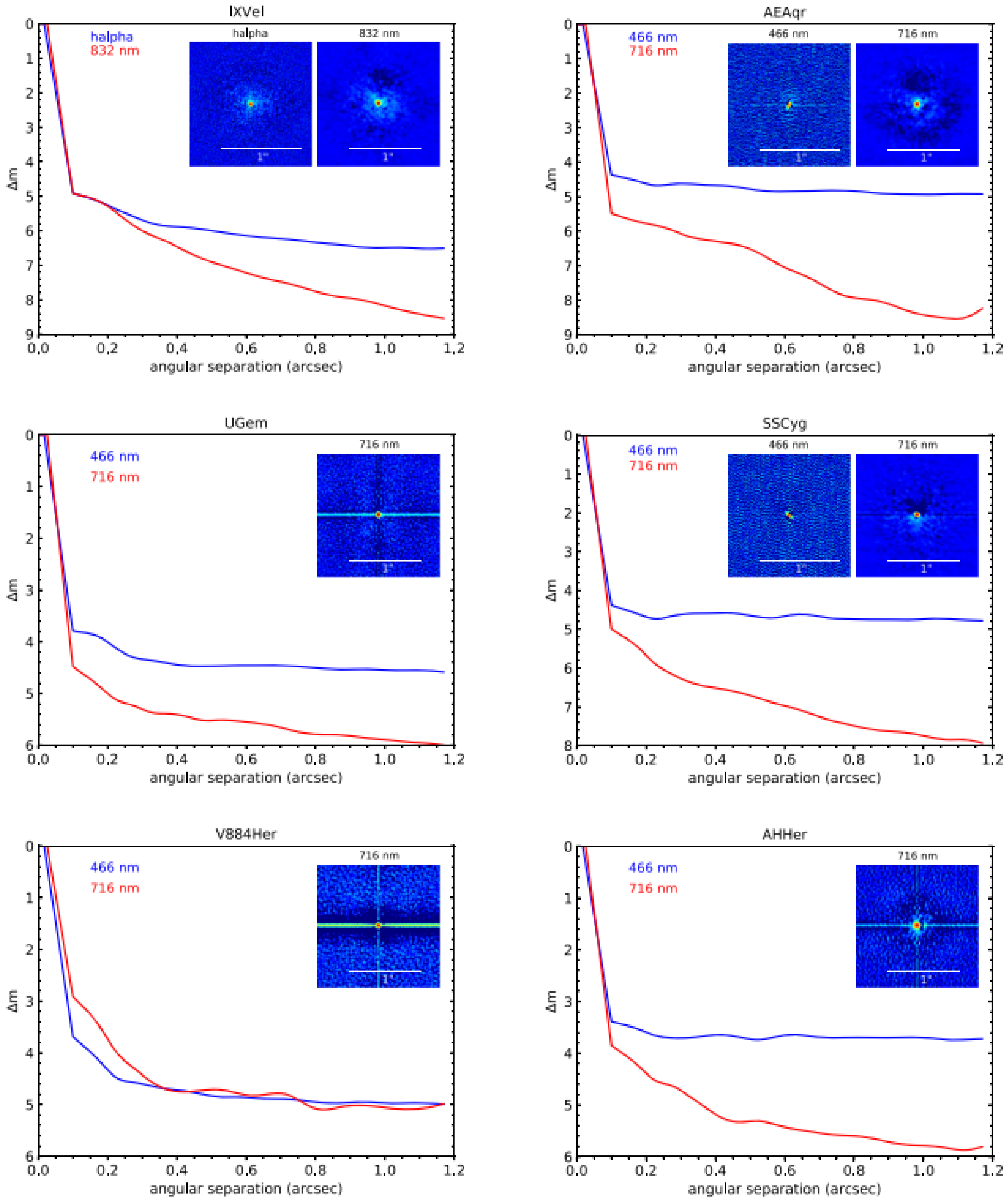
Figure 3. H-band image of V471 Tau obtained on the SPHERE IRDIS instrument at VLT. Left panel: resulting image after angular differential imaging (ADI). The area in-between the white circles denotes the 5σ predicted position of the brown dwarf. Right panel: contrast curves obtained via two different methods of fake companion injection (see the text for details). The vertical lines again denote the predicted position of the object with the diamond denoting the predicted contrast of a first generation brown dwarf.

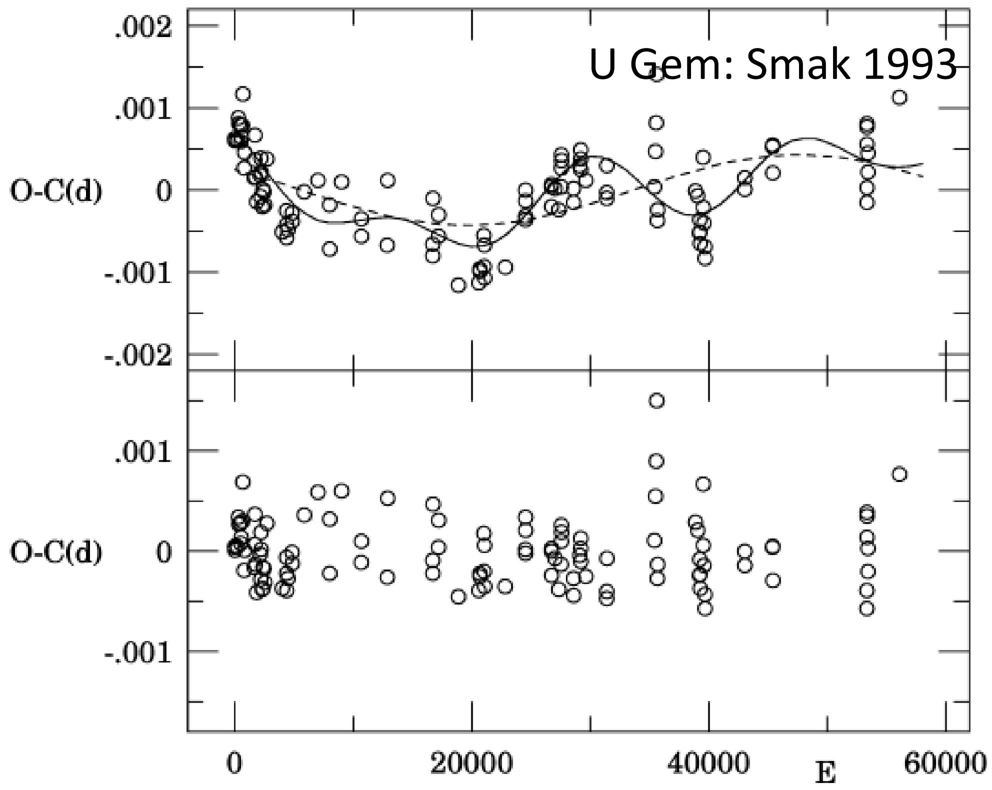
* Zsolt Kővári’s talk on its magnetic activity!

* Pulsation timings do not follow ETVs either (Vanderbosch et al. 2016)

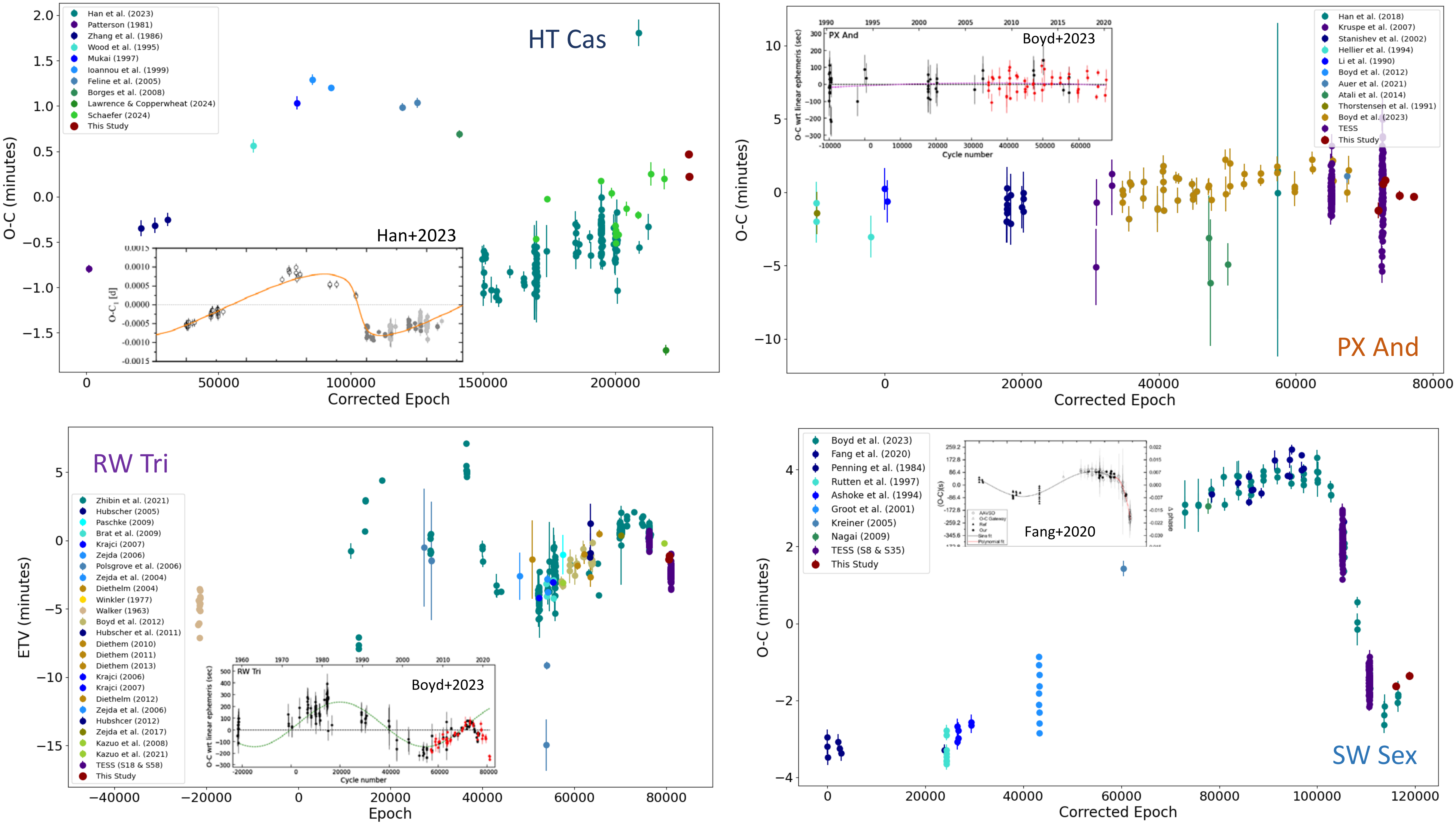
V471 Tau: Direct imaging potential (Hardy et al. 2015)

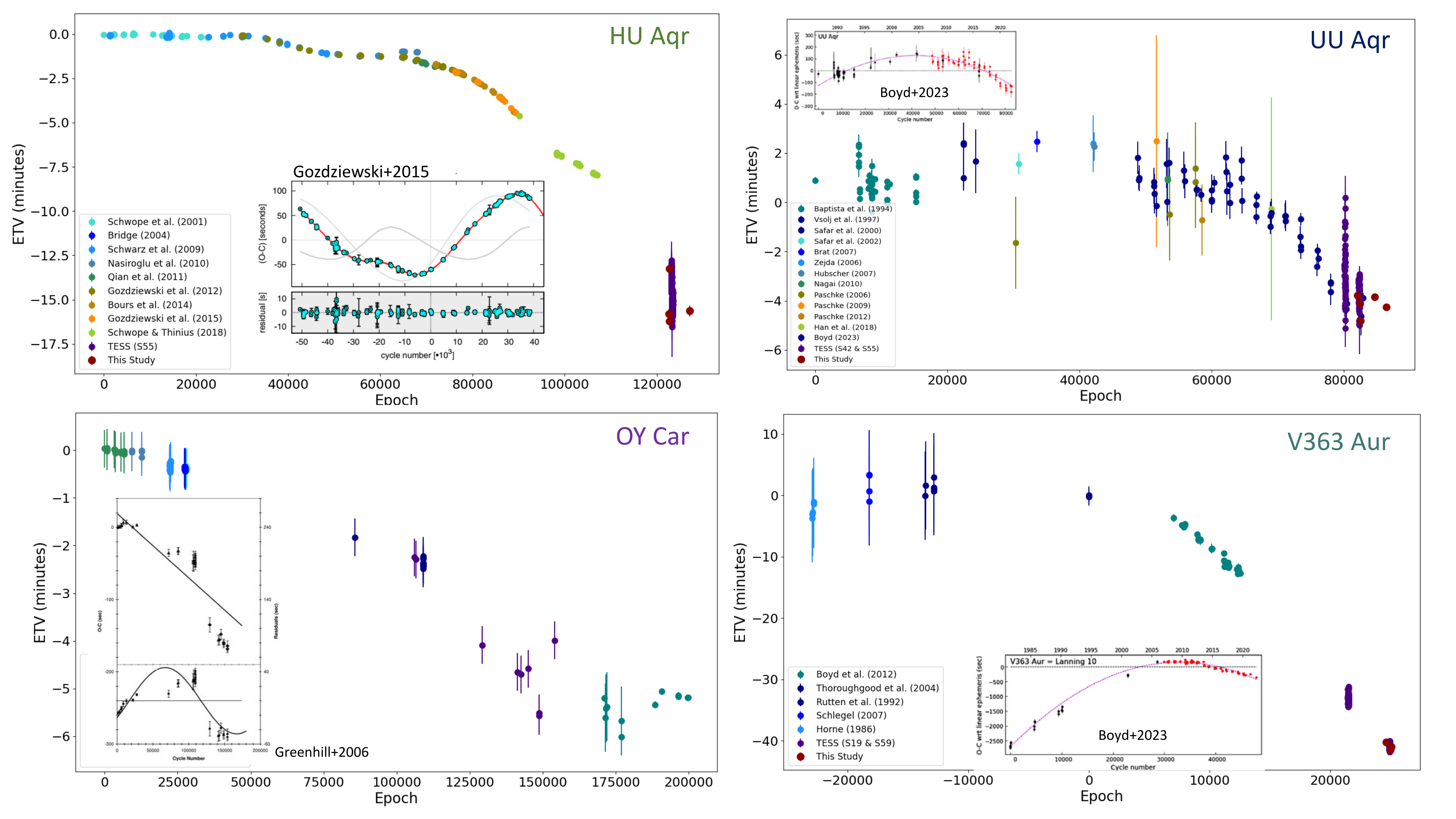
Shara et al. (2021)
Speckle imaging observations of
CVs with Gemini-S & N:
No MS components earlier than
M4V at 2-100 AU (3-1000 yrs)





The mass transfer rate fluctuates by 20-30% in 10 years estimated based on number of outbursts and mean flux changes in 3 year-intervals, which do not correlate with the observed orbital period variation. " .. it would be interesting to check the mechanism proposed by Applegate (1992)"


HT Cas
O-C (minutes)
Corrected Epoch
Han et al. (2023)
Patterson (1981)
Zhang et al. (1986)
Wood et al. (1995)
Mukai (1997)
Ioannou et al. (1999)
Feline et al. (2005)
Borges et al. (2008)
Lawrence & Copperwheat (2024)
Schaefer (2024)
This Study
Han+2023
O-C$_1$ [d]
PX And
Boyd+2023
O-C wrt linear ephemeris (sec)
Cycle number
Han et al. (2018)
Kruspe et al. (2007)
Stanishev et al. (2002)
Hellier et al. (1994)
Li et al. (1990)
Boyd et al. (2012)
Auer et al. (2021)
Atali et al. (2014)
Thorstensen et al. (1991)
Boyd et al. (2023)
TESS
This Study
RW Tri
ETV (minutes)
Epoch
Zhibin et al. (2021)
Hubscher (2005)
Paschke (2009)
Brat et al. (2009)
Krajci (2007)
Zejda (2006)
Polsgrove et al. (2006)
Zejda et al. (2004)
Diethelm (2004)
Winkler (1977)
Walker (1963)
Boyd et al. (2012)
Hubscher et al. (2011)
Diethem (2010)
Diethem (2011)
Diethem (2013)
Krajci (2006)
Krajci (2007)
Diethelm (2012)
Zejda et al. (2006)
Hubshcer (2012)
Zejda et al. (2017)
Kazuo et al. (2008)
Kazuo et al. (2021)
TESS (S18 & S58)
This Study
Boyd+2023
SW Sex
O-C (minutes)
Corrected Epoch
Boyd et al. (2023)
Fang et al. (2020)
Penning et al. (1984)
Rutten et al. (1997)
Ashoke et al. (1994)
Groot et al. (2001)
Kreiner (2005)
Nagai (2009)
TESS (S8 & S35)
This Study
Fang+2020



HU Aqr
Gozdziewski+2015
ETV (minutes)
Epoch
Schwope et al. (2001)
Bridge (2004)
Schwarz et al. (2009)
Nasiroglu et al. (2010)
Qian et al. (2011)
Gozdziewski et al. (2012)
Bours et al. (2014)
Gozdziewski et al. (2015)
Schwope & Thinius (2018)
TESS (S55)
This Study
UU Aqr
Boyd+2023
Baptista et al. (1994)
Vsolj et al. (1997)
Safar et al. (2000)
Safar et al. (2002)
Brat (2007)
Zejda (2006)
Hubscher (2007)
Nagai (2010)
Paschke (2006)
Paschke (2009)
Paschke (2012)
Han et al. (2018)
Boyd (2023)
TESS (S42 & S55)
This Study
OY Car
Greenhill+2006
V363 Aur
Boyd+2023
Boyd et al. (2012)
Thoroughgood et al. (2004)
Rutten et al. (1992)
Schlegel (2007)
Horne (1986)
TESS (S19 & S59)
This Study

1. Measurements of Eclipse Timings (methods, packages, pulsations, CVs …) ?

2. Underestimated error bars

3. Heteroscedasticity in the ETV data

4. Noise sources?

5. Uncertainties bring eccentriciy

6. Parameter degeneracies?

7. Long Baseline of the ETVs

Crazy Questions in My Head!

Crazy Questions in My Head Vol-2

8. What aboud dM?
What about q?
What about activity?

9. Naive (yet improving) understanding of quadruple moment changes

10. Secular changes in HW Vir-like systems?

11. CVs: Hot spots, disks, accretion, variable mass transfer…

Summary & Final Remarks

- ✓ Slight changes in the ETV models can make the systems stable!
- ✓ The energy in the dM is not sufficient for the observed ETVs in most cases!
- ✓ Combined models should be experimented (with e ~ 0)
- ✓ Predicted radial velocity amplitudes are smaller than the errors in V_γ
- ✓ Planets in close binaries with PCEB progenitors might survive the common envelope ejection (Kostov et al. 2016)
- ✓ There are first & second generation as well as hybrid explanations for planets
- ✓ Precise observations on longer baselines are needed
- ✓ A larger sample of eclipsing PCEB will help population statistics
- ✓ CVs are complicated for many reasons
- ✓ Even if the planets are not real, ETVs are and they are waiting to be explained!

We thank

TÜBİTAK for their support with 122F358

YÖK & **AÜ BAP** for their support with FBA-2023-2698

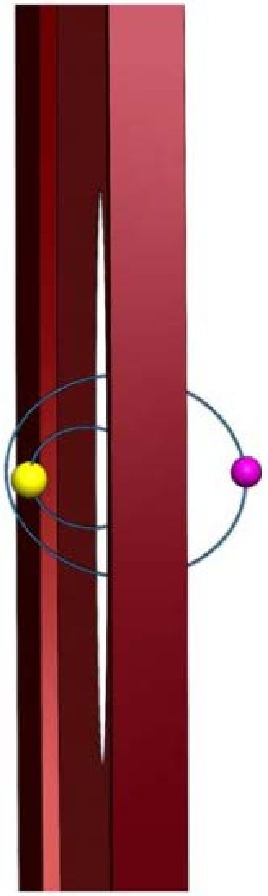
Organizers of the

Binary and Multiple Stars in the Era of Big Sky Surveys

And YOU for your attention!

AC Her: Evidence of the First Polar Circumbinary Planet

Martin et al. (2023)



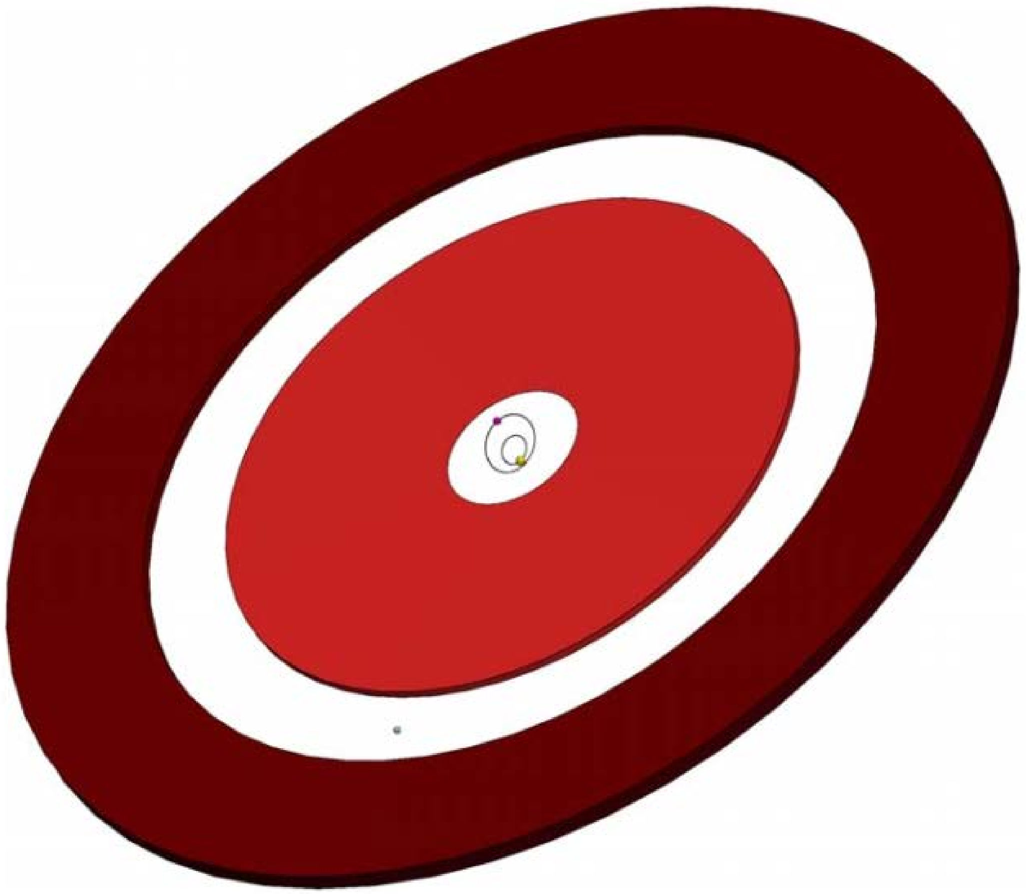


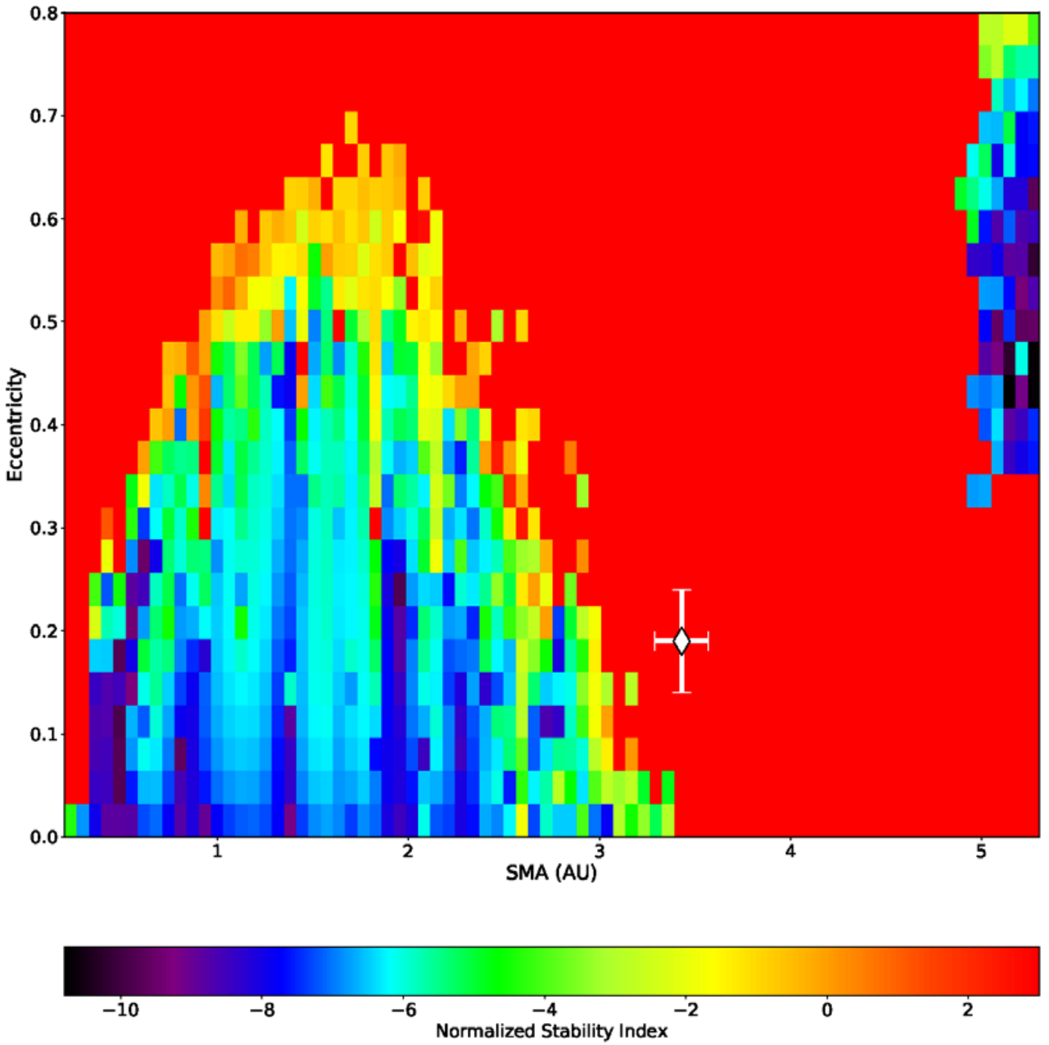
Table 1
Parameters of the AC Her Binary Star System

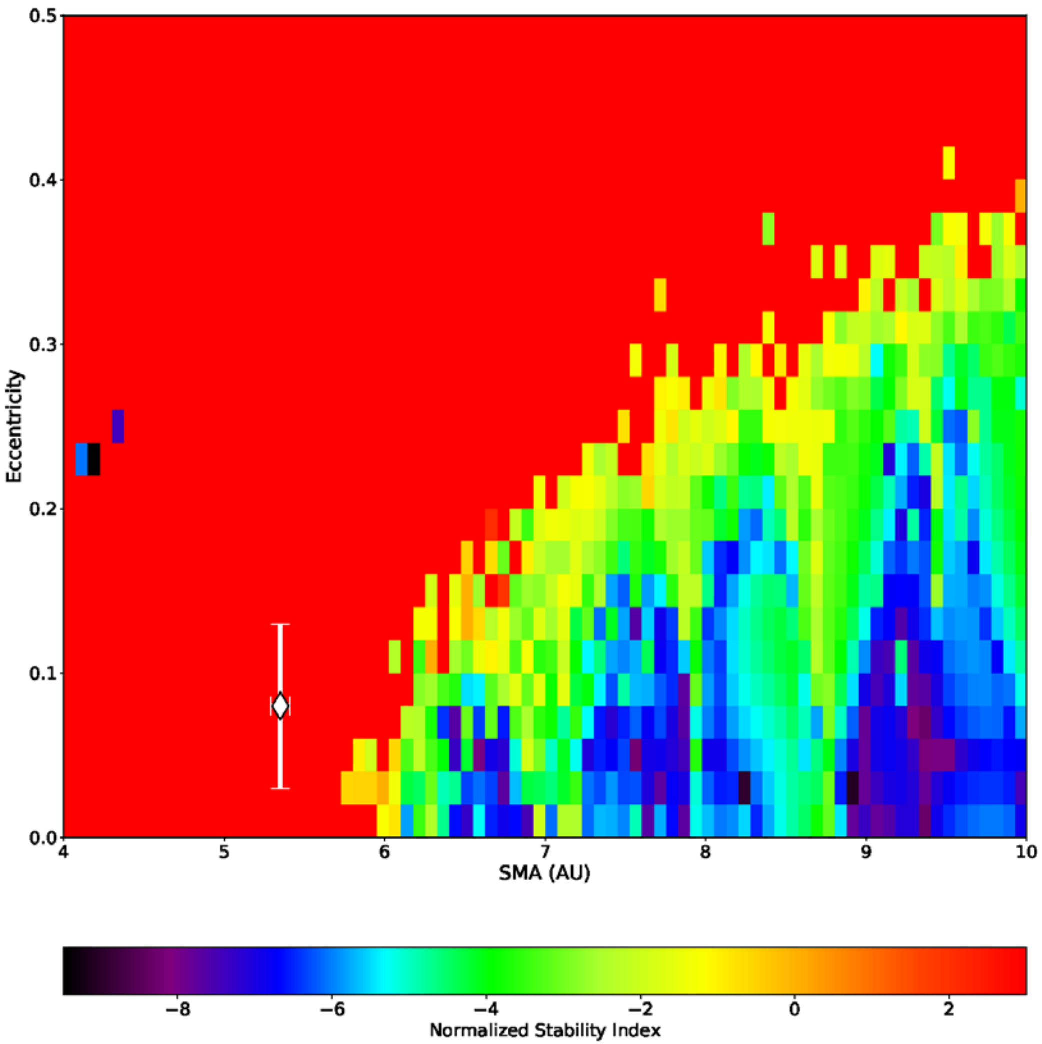
Parameters of the AC Her System	Symbol	Value	Uncertainty
Binary star parameters from Anugu et al. (2023)			
Mass of post-AGB star	M_1	0.73 $M_\odot$	$\pm$0.13 $M_\odot$
Mass of companion star	M_2	1.4 $M_\odot$	$\pm$0.12 $M_\odot$
Binary semimajor axis	a_b	2.83 au	$\pm$0.08 au
Binary eccentricity	e_b	0.206	$\pm$0.004
Binary inclination	i_b	$142\overset{\circ}{.}9$	$\pm 1\overset{\circ}{.}1$
Binary longitude of ascending node	Ω_b	$155\overset{\circ}{.}1$	$\pm 1\overset{\circ}{.}8$
Binary argument of periastron	ω_b	$118\overset{\circ}{.}6$	$\pm 2^\circ$
Disk parameters from Hillen et al. (2015)			
Disk inclination	i_d	50°	$\pm$8°
Disk longitude of ascending node	Ω_d	125°	$\pm$10°
Quantities calculated in this work			
Inclination of disk relative to binary	i_{bd}	$96\overset{\circ}{.}5$	⋯
Longitude of ascending node of disk relative to binary	Ω_{bd}	$84\overset{\circ}{.}1$	⋯
Inclination of the disk relative to the binary eccentricity vector	i_{polar}	$8\overset{\circ}{.}7$	⋯

AC Her is a post-AGB star with a polar disk with a (potential) planet in it.

NN Ser

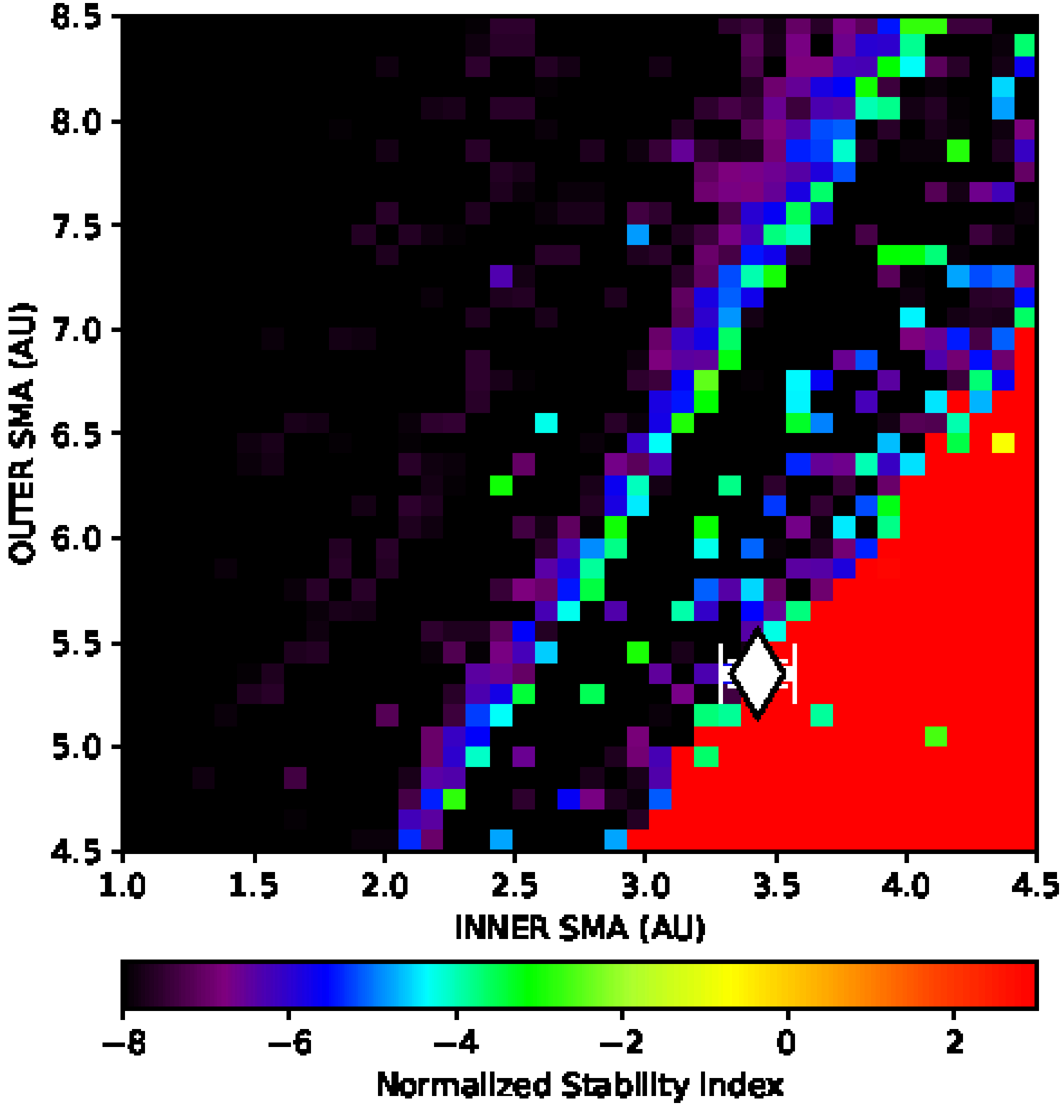
ETV Solution: Marsh et al. (2014)





1. Outer companion is fixed while the inner (a,e) is free
Data point indicates the position of the inner from ETV

2. Inner companion is fixed while the outer (a,e) is free
Data point indicates the position of the outer from ETV



NN Ser: The **eccentricites are fixed to zero**

All other parameters from the ETV solution are fixed.

Crucial Note: Hardy et al. (2016) observed the evidence of a dust disk with ALMA!

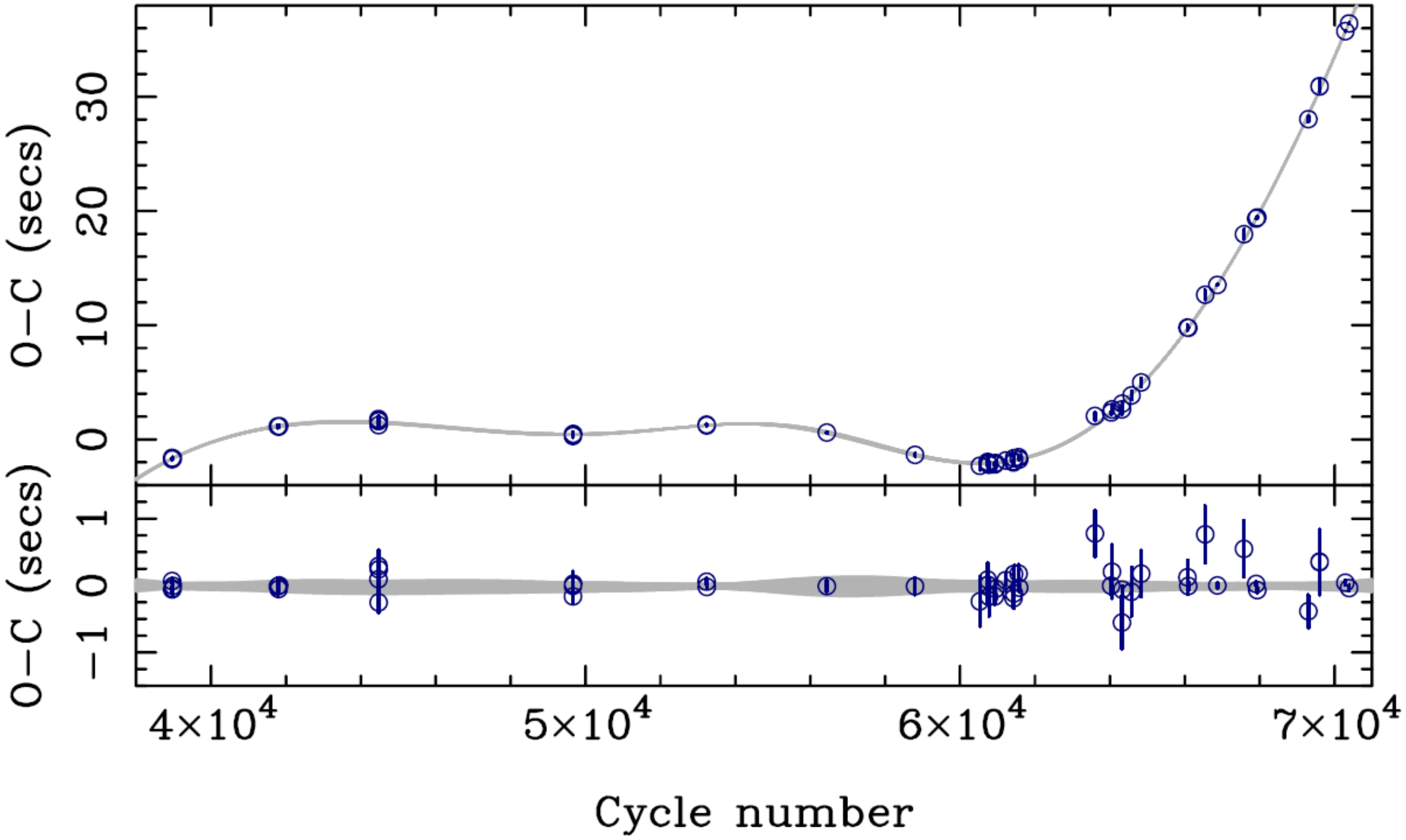
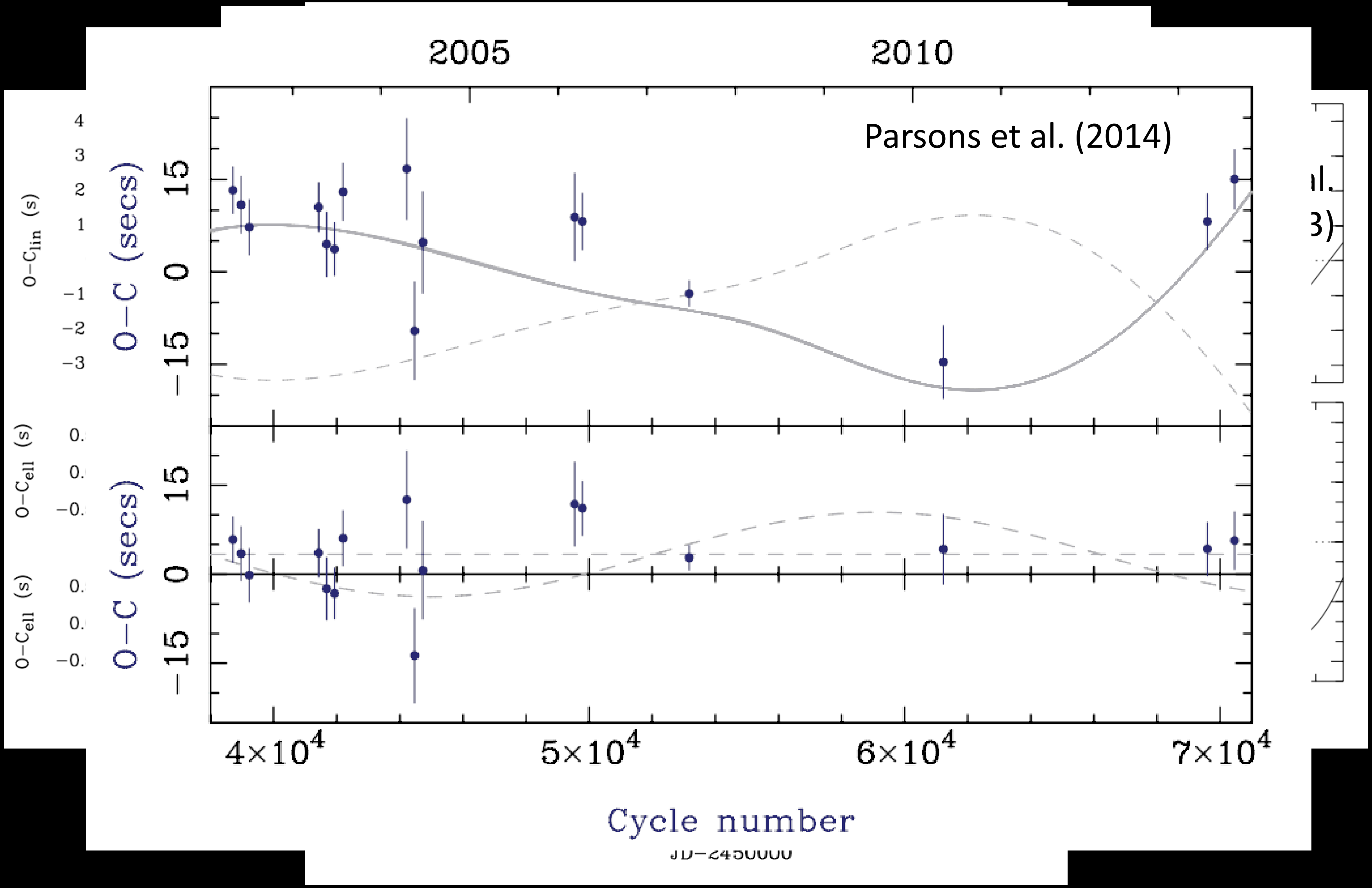


Figure 3. This plot is identical to Fig. 2 but now the orbital fits are based upon all data, incorporating the new times and it includes a plot of the residuals relative to the best of the orbits shown. For clarity, only points with uncertainties <0.5 s are shown.

Marsh et al. (2014)

‘Different Data, Different Solutions, Different Planets?’
NN Ser



‘Different Data, Different Solutions, Different Planets?’
HW Virgo