A Search for Exoplanets in Short-Period Binary Star Systems

Ron Kaitchuck, Garrison Turner, Joe Childers

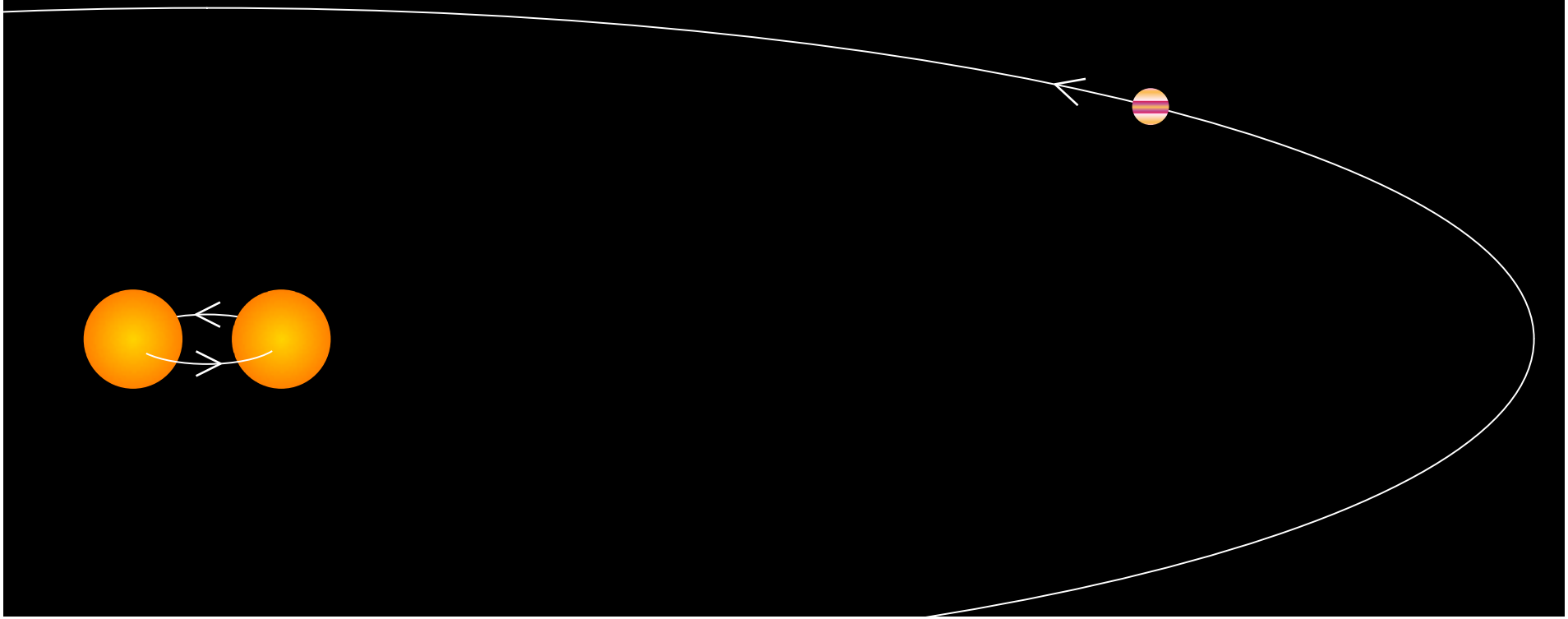
Ball State University

Planets in Binary Stars

- More than 40 binaries with planets known.
- These are all wide binaries; stellar orbital periods of decades or more.
- The planets can be either circumbinary (p-type) or circumstellar (s-type).

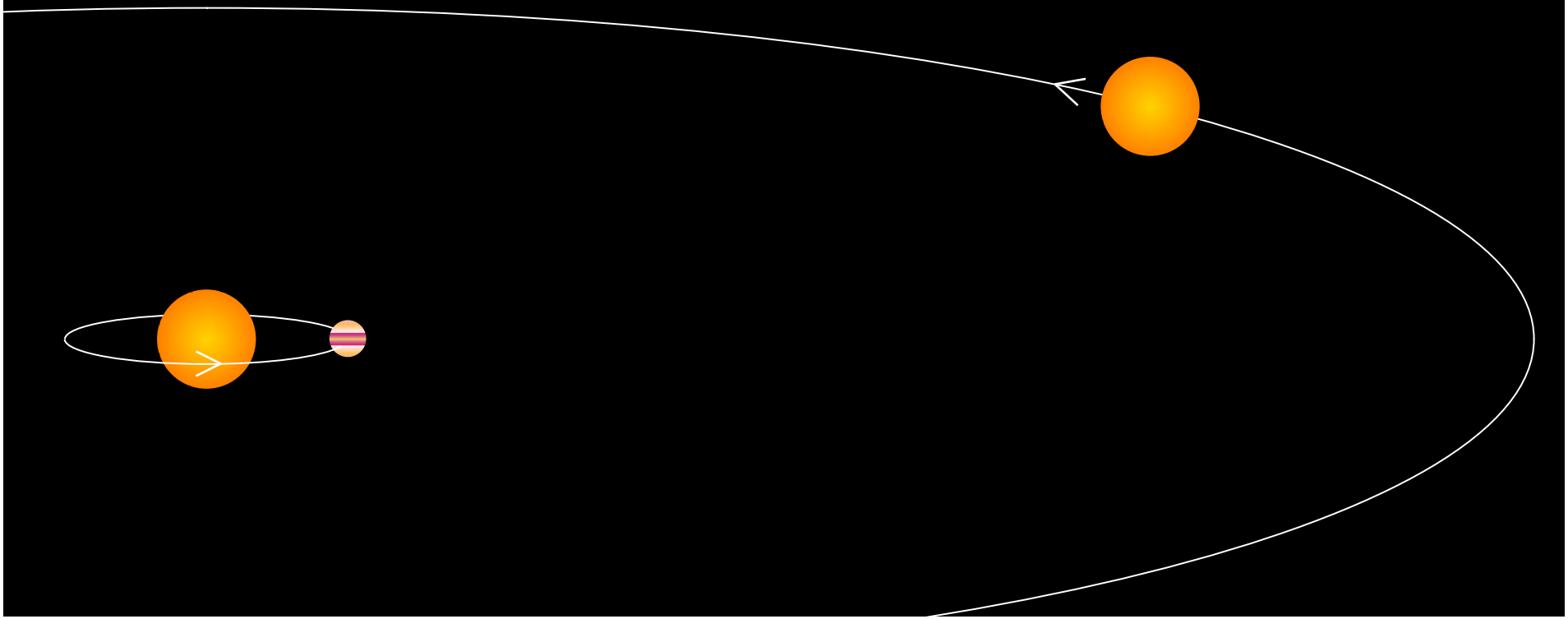
Planetary Orbits

Circumbinary (p-type) orbits



Planetary Orbits

Circumstellar (s-type) orbits



Planets in Binary Stars

The formation of planets in binary stars is modeled by core accretion or disk instability theory.

Core accretion models indicate that planets with s-type orbits will not form if the stars are closer than ~ 20 AU. But …

- γ Cep and HD196885 have planets and are at this limit.
- HR 7162 is inside this limit (19 AU) with a planet 2 AU from one star. Disk instability formation mechanism?

Can planets form in even more compact binaries?

The Program

In 2006 we began a search for planets with s-type orbits in much shorter-period binaries.

γ Cep has an orbital period of 57 years.

Our stars have periods of a few days (a < 1 AU)!

The Program

Reasons not to do this program:

- Guaranteed a null result (?)
- Need for lots of telescope time
- Open-ended search?

The Program

On the other hand –

- This really should be checked.
- There may be other ways planets can form in binary systems, e.g. as a product of mass transfer?
- Planets have been found in even stranger environments – around pulsars.

Transit Search in Eclipsing Binary Stars

Orbital planes of planets likely matches that of the stars, so planet transits are very likely if planets exist.

The possible range of planetary orbital periods can be predicted – so we will know when we have looked long enough.

Null detections can establish a lack of planets above a certain size.

Transit Search in Eclipsing Binary Stars

Wouldn't transits have already been discovered?

- Historically most light curve data were photographic or from a single-channel PMT.
- Usually the data was phase averaged.
- No one was looking for this.

Transit Search in Eclipsing Binary Stars

Disadvantage –

- the combined light of two stars makes the transit a bit harder to see.
- Eclipse phases are less useful.
- Few targets with periods beyond 20 days.

Target Selection

- Eclipsing, main sequence stars
- Detached – clean, stable light curves
- Physical parameters are known
- Maximum stable planetary period > 0.5 days
- The combined stellar luminosities allow a Jupiter-sized planet to produce ≥ 3 millimag drop.

[Branewicz and Dworak catalog]

Planetary Orbital Periods

The inner Roche tidal limit sets the shortest possible orbital period.

We derived the size of the largest *stable* planetary orbit from a study by Cuntz et. al. 2007.

This sets the longest planetary orbital period.

Most Studied Targets

Name	Binary Period (days)	Binary Semi-Major (R_{Sun})	Mass (M_{sun})	Radius (R_{sun})	Temp. (K)	% Roche Lobe Filled	Min. Planet Radius (R_{Jup})	Max. Planet Period days)
FO ORI A	18.80	45.90	2.19	1.87	8900	10	1.06	3.61
FO Ori B			1.49	1.10	6840	7	1.79	3.27
V541 Cyg A	15.34	47.18	3.27	1.89	9510	10	1.42	2.89
V541 Cyg B			2.78	1.89	9510	11	1.42	2.72
DF Peg A	14.70	42.49	2.87	2.16	8610	12	1.47	2.84
DF Peg B			1.90	3.15	6340	22	1.35	0.98
BW Aqr A	6.72	20.6	1.37	1.13	5990	14	0.72	0.95
BW Aqr B			1.23	0.82	5660	11	0.80	0.90
HS Aur A	4.91	14.73	1.01	0.74	5350	12	0.51	0.93
HS Aur B			0.77	0.65	5180	12	0.54	0.86
WZ Oph A	4.18	14.32	1.14	1.35	6100	25	1.01	0.78
WZ Oph B			1.11	1.32	6130	24	1.00	0.75
BS Dra A	3.36	12.83	1.47	1.03	6420	20	0.75	0.64
BS Dra B			1.04	0.64	7900	14	0.50	0.59

Less Studied Targets

EK Cep

V477 Cyg

V1143 Cyg

TZ CMi

AL Leo

TV Nor

V535 Oph

Precision Photometry

We need photometric precision of 0.5% or better.

This requires:

- Very careful image processing
- CCD ensemble differential photometry.
- A willingness to throw out lots of *nights* of data.

Telescopes

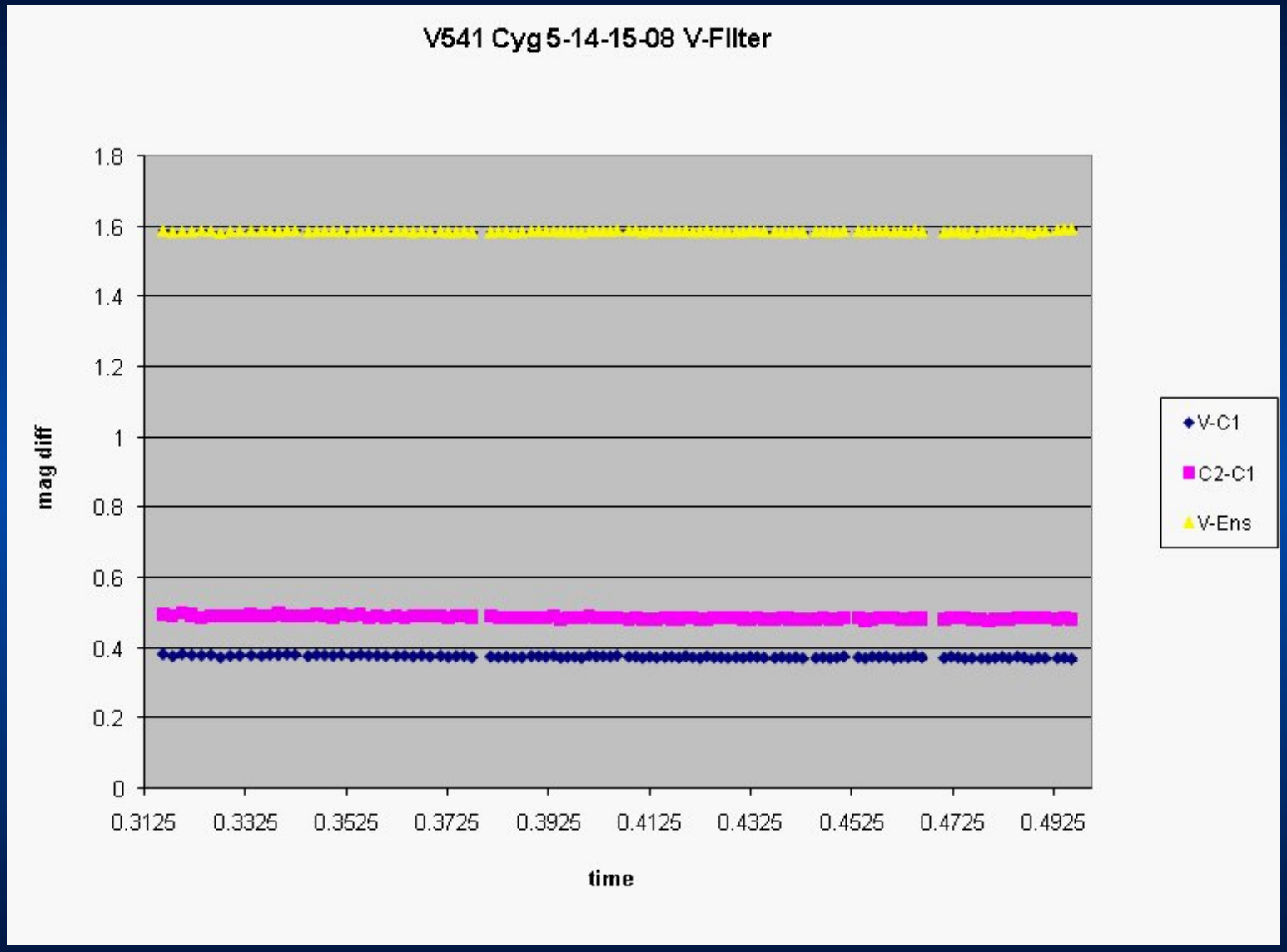
SARA

- 0.9 meter, Kitt Peak (remotely operated)
- 0.6 meter, CTIO (remotely operated)

BSU Observatory

- 0.4 meter, SC (autonomous)
- 0.35 meter, SC


OBJECTS IN MIRROR ARE
FARTHER THAN THEY APPEAR
310
E
EXIT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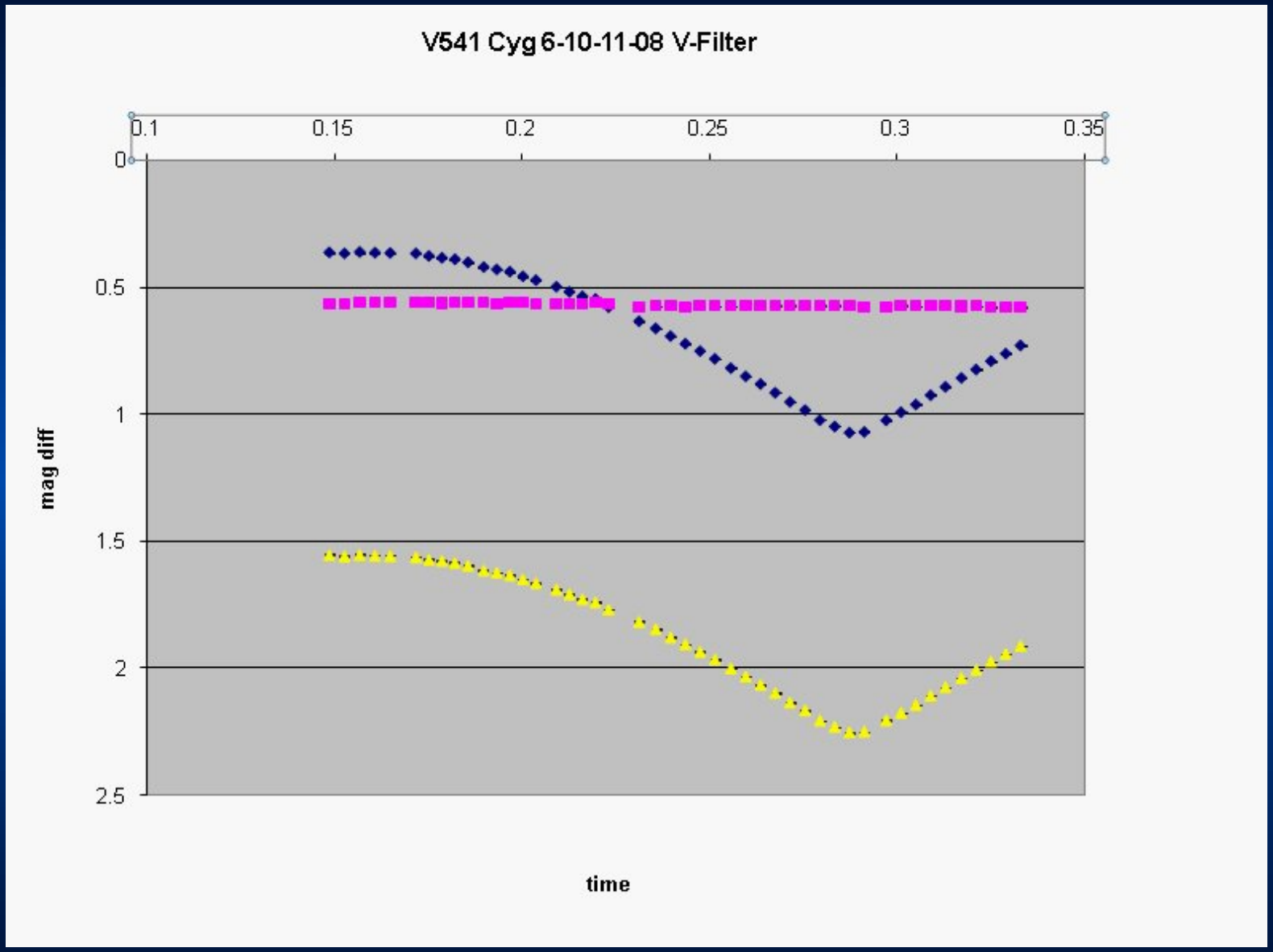
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.3125
0.3325
0.3525
0.3725
0.3925
0.4125
0.4325
0.4525
0.4725
0.4925
time
V-C1
C2-C1
V-Ens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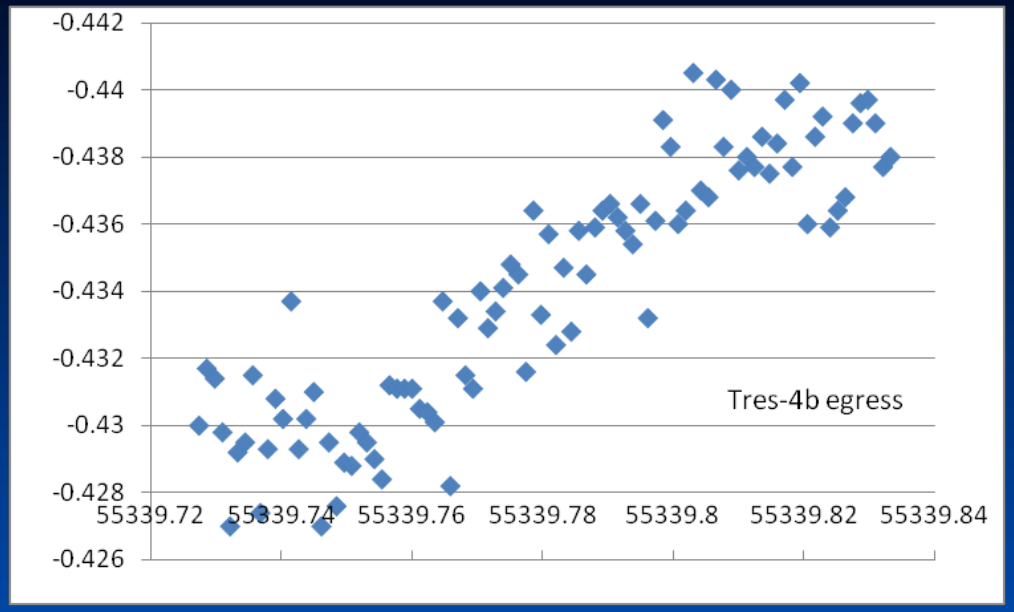
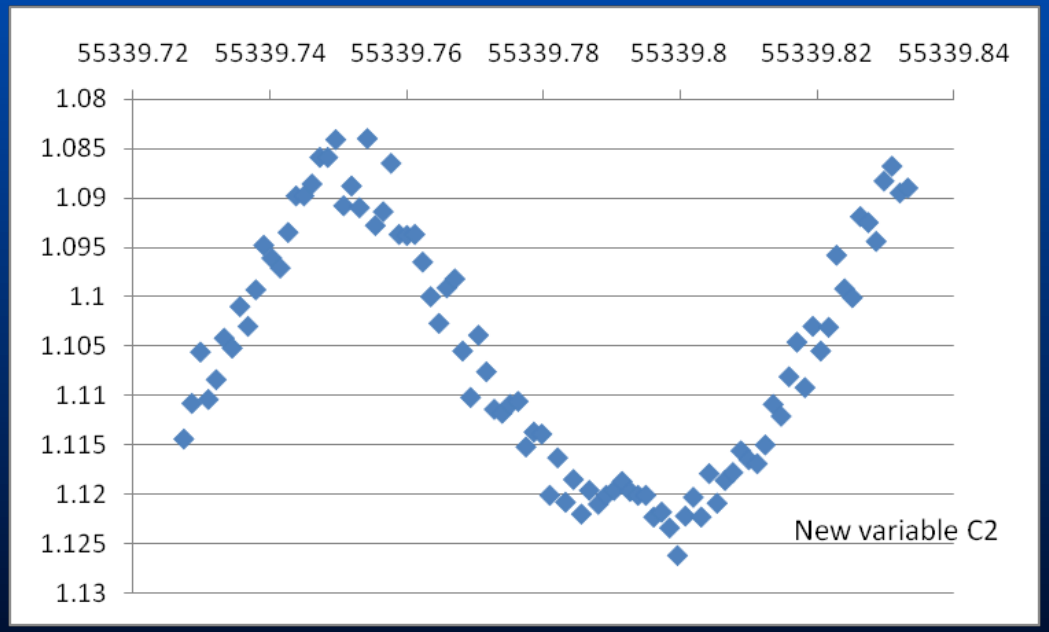
0
0.5
1
1.5
2
2.5
mag diff
time

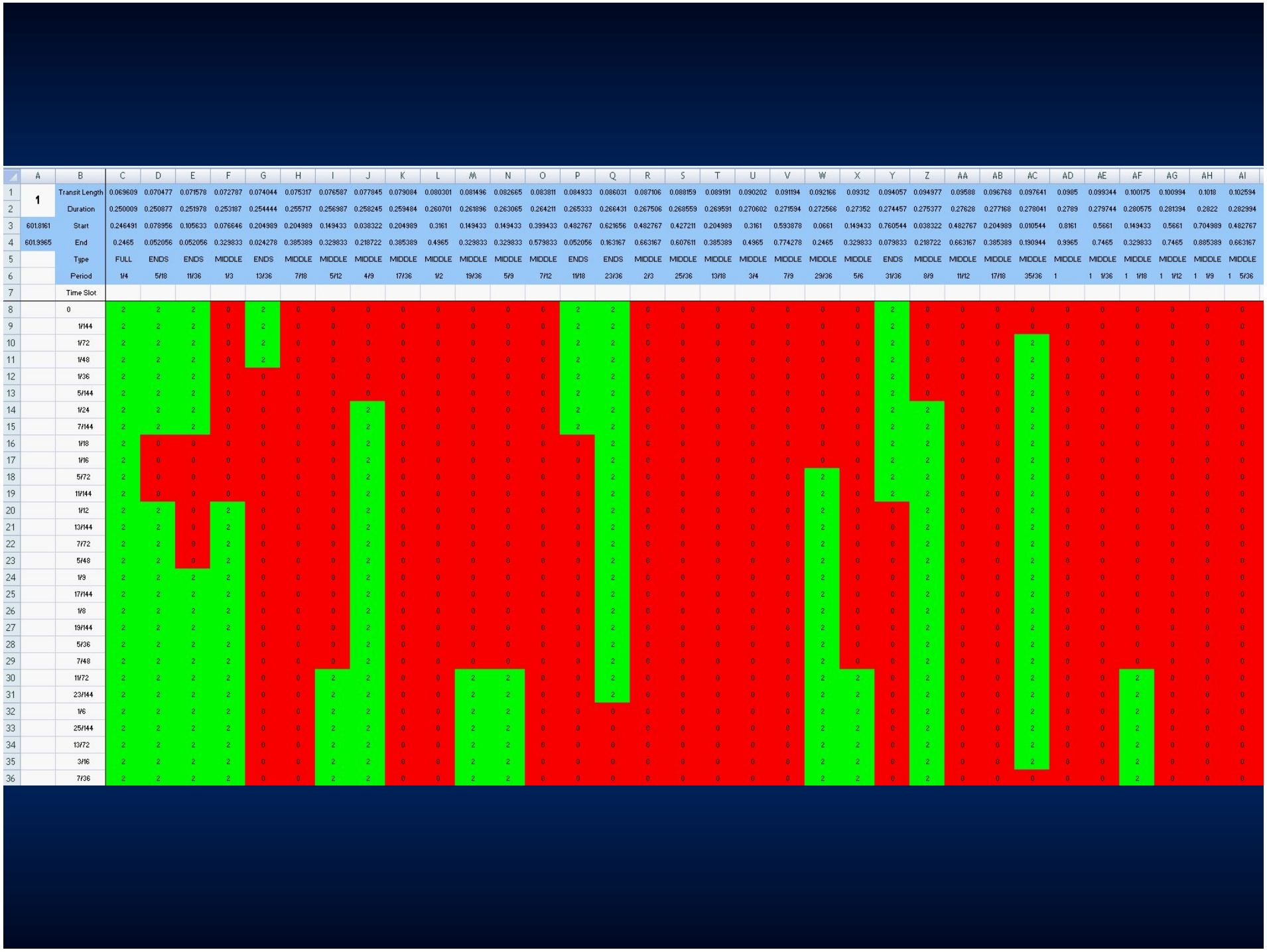

-0.442
-0.44
-0.438
-0.436
-0.434
-0.432
-0.43
-0.428
-0.426
55339.72
55339.74
55339.76
55339.78
55339.8
55339.82
55339.84
Tres-4b egress


55339.72
55339.74
55339.76
55339.78
55339.8
55339.82
55339.84
1.08
1.085
1.09
1.095
1.1
1.105
1.11
1.115
1.12
1.125
1.13
New variable C2

Coverage

The goal is to obtain good phase coverage over the range of possible orbital periods.

For each night the times of observations are entered in a 2-D phase vs. periods spreadsheet.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI
1	1	Transit Length	0.069609	0.070477	0.071578	0.072787	0.074044	0.075317	0.076587	0.077845	0.079084	0.080301	0.081496	0.082665	0.083811	0.084933	0.086031	0.087106	0.088159	0.089191	0.090202	0.091194	0.092166	0.09312	0.094057	0.094977	0.09588	0.096768	0.097641	0.0985	0.099344	0.100175	0.100994	0.1018	0.102594
2		Duration	0.250009	0.250877	0.251978	0.253187	0.254444	0.255717	0.256987	0.258245	0.259484	0.260701	0.261896	0.263065	0.264211	0.265333	0.266431	0.267506	0.268559	0.269591	0.270602	0.271594	0.272566	0.27352	0.274457	0.275377	0.27628	0.277168	0.278041	0.2789	0.279744	0.280575	0.281394	0.2822	0.282994
3	601.8161	Start	0.246491	0.078956	0.105633	0.076646	0.204989	0.204989	0.149433	0.038322	0.204989	0.3161	0.149433	0.149433	0.399433	0.482767	0.621656	0.482767	0.427211	0.204989	0.3161	0.593878	0.0661	0.149433	0.760544	0.038322	0.482767	0.204989	0.010544	0.8161	0.5661	0.149433	0.5661	0.704989	0.482767
4	601.9965	End	0.2465	0.052056	0.052056	0.329833	0.024278	0.385389	0.329833	0.218722	0.385389	0.4965	0.329833	0.329833	0.579833	0.052056	0.163167	0.663167	0.607611	0.385389	0.4965	0.774278	0.2465	0.329833	0.079833	0.218722	0.663167	0.385389	0.190944	0.9965	0.7465	0.329833	0.7465	0.885389	0.663167
5		Type	FULL	ENDS	ENDS	MIDDLE	ENDS	MIDDLE	MIDDLE	MIDDLE	MIDDLE	MIDDLE	MIDDLE	MIDDLE	MIDDLE	ENDS	ENDS	MIDDLE	MIDDLE	MIDDLE	MIDDLE	MIDDLE	MIDDLE	MIDDLE	ENDS	MIDDLE	MIDDLE	MIDDLE	MIDDLE	MIDDLE	MIDDLE	MIDDLE	MIDDLE	MIDDLE	MIDDLE	MIDDLE
6		Period	1/4	5/18	11/36	1/3	13/36	7/18	5/12	4/9	17/36	1/2	19/36	5/9	7/12	11/18	23/36	2/3	25/36	13/18	3/4	7/9	29/36	5/6	31/36	8/9	11/12	17/18	35/36	1	1 1/36	1 1/18	1 1/12	1 1/9	1 5/36
7		Time Slot																																	
8		0	2	2	2	0	2	0	0	0	0	0	0	0	0	2	2	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0
9		1/144	2	2	2	0	2	0	0	0	0	0	0	0	0	2	2	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0
10		1/72	2	2	2	0	2	0	0	0	0	0	0	0	0	2	2	0	0	0	0	0	0	0	2	0	0	0	2	0	0	0	0	0	0
11		1/48	2	2	2	0	2	0	0	0	0	0	0	0	0	2	2	0	0	0	0	0	0	0	2	0	0	0	2	0	0	0	0	0	0
12		1/36	2	2	2	0	0	0	0	0	0	0	0	0	0	2	2	0	0	0	0	0	0	0	2	0	0	0	2	0	0	0	0	0	0
13		5/144	2	2	2	0	0	0	0	0	0	0	0	0	0	2	2	0	0	0	0	0	0	0	2	0	0	0	2	0	0	0	0	0	0
14		1/24	2	2	2	0	0	0	0	2	0	0	0	0	0	2	2	0	0	0	0	0	0	0	2	2	0	0	2	0	0	0	0	0	0
15		7/144	2	2	2	0	0	0	0	2	0	0	0	0	0	2	2	0	0	0	0	0	0	0	2	2	0	0	2	0	0	0	0	0	0
16		1/18	2	0	0	0	0	0	0	2	0	0	0	0	0	0	2	0	0	0	0	0	0	0	2	2	0	0	2	0	0	0	0	0	0
17		1/16	2	0	0	0	0	0	0	2	0	0	0	0	0	0	2	0	0	0	0	0	0	0	2	2	0	0	2	0	0	0	0	0	0
18		5/72	2	0	0	0	0	0	0	2	0	0	0	0	0	0	2	0	0	0	0	0	2	0	2	2	0	0	2	0	0	0	0	0	0
19		11/144	2	0	0	0	0	0	0	2	0	0	0	0	0	0	2	0	0	0	0	0	2	0	2	2	0	0	2	0	0	0	0	0	0
20		1/12	2	2	0	2	0	0	0	2	0	0	0	0	0	0	2	0	0	0	0	0	2	0	0	2	0	0	2	0	0	0	0	0	0
21		13/144	2	2	0	2	0	0	0	2	0	0	0	0	0	0	2	0	0	0	0	0	2	0	0	2	0	0	2	0	0	0	0	0	0
22		7/72	2	2	0	2	0	0	0	2	0	0	0	0	0	0	2	0	0	0	0	0	2	0	0	2	0	0	2	0	0	0	0	0	0
23		5/48	2	2	0	2	0	0	0	2	0	0	0	0	0	0	2	0	0	0	0	0	2	0	0	2	0	0	2	0	0	0	0	0	0
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25		17/144	2	2	2	2	0	0	0	2	0	0	0	0	0	0	2	0	0	0	0	0	2	0	0	2	0	0	2	0	0	0	0	0	0
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27		19/144	2	2	2	2	0	0	0	2	0	0	0	0	0	0	2	0	0	0	0	0	2	0	0	2	0	0	2	0	0	0	0	0	0
28		5/36	2	2	2	2	0	0	0	2	0	0	0	0	0	0	2	0	0	0	0	0	2	0	0	2	0	0	2	0	0	0	0	0	0
29		7/48	2	2	2	2	0	0	0	2	0	0	0	0	0	0	2	0	0	0	0	0	2	0	0	2	0	0	2	0	0	0	0	0	0
30		11/72	2	2	2	2	0	0	2	2	0	0	2	2	0	0	2	0	0	0	0	0	2	2	0	2	0	0	2	0	0	2	0	0	0
31		23/144	2	2	2	2	0	0	2	2	0	0	2	2	0	0	2	0	0	0	0	0	2	2	0	2	0	0	2	0	0	2	0	0	0
32		1/6	2	2	2	2	0	0	2	2	0	0	2	2	0	0	0	0	0	0	0	0	2	2	0	2	0	0	2	0	0	2	0	0	0
33		25/144	2	2	2	2	0	0	2	2	0	0	2	2	0	0	0	0	0	0	0	0	2	2	0	2	0	0	2	0	0	2	0	0	0
34		13/72	2	2	2	2	0	0	2	2	0	0	2	2	0	0	0	0	0	0	0	0	2	2	0	2	0	0	2	0	0	2	0	0	0
35		3/16	2	2	2	2	0	0	2	2	0	0	2	2	0	0	0	0	0	0	0	0	2	2	0	2	0	0	2	0	0	2	0	0	0
36		7/36	2	2	2	2	0	0	2	2	0	0	2	2	0	0	0	0	0	0	0	0	2	2	0	2	0	0	0	0	0	2	0	0	0

	A	B	C	D	E	F	G	H	I	J	K
1	**Star**				**Observations**			2454			
2	**V 541 Cyg A**				**Start**	**End**	**Duration**	**35.9%**			
3	**Catalog Stellar Properties**			1	601.8161	601.9965	4:19	0.375378	0.003139	V	
4	This Star's Mass (M_S)	3.21		2	615.7509	615.8792	3:04	0.358164	0.002847	V	
5	Companion's Mass (M_S)	2.78		3	623.6222	623.8389	5:12	0.363872	0.005262	V	
6	Separation (R_S)	47.18		4	671.6423	671.8149	4:08	0.360251	0.005701	V	
7	Eccentricity	0.00									
8	This Star's Radius (R_S)	1.89									
9	**Calculated Stellar Properties**										
10	q	0.87									
11	Sepration at Periastron	47.18									
12	Maximum Stable Semimajor	12.59									
13	Maximum Planetary Period (d)	2.89									
14	This Star's Density ($M_S\ R_S^{-3}$)	0.11									
15	**Spreadsheet Calculations**										
16	Period Step (h:m)	0:40									
17											
18	**Proposed Observation**										
19	Start										
20	End										
21	Duration										
22	New Observations										
23	Repeat Observations										
24	Gain in Total Coverage	#VALUE!									
25	Final Coverage										
26											
27											

Results - Coverage

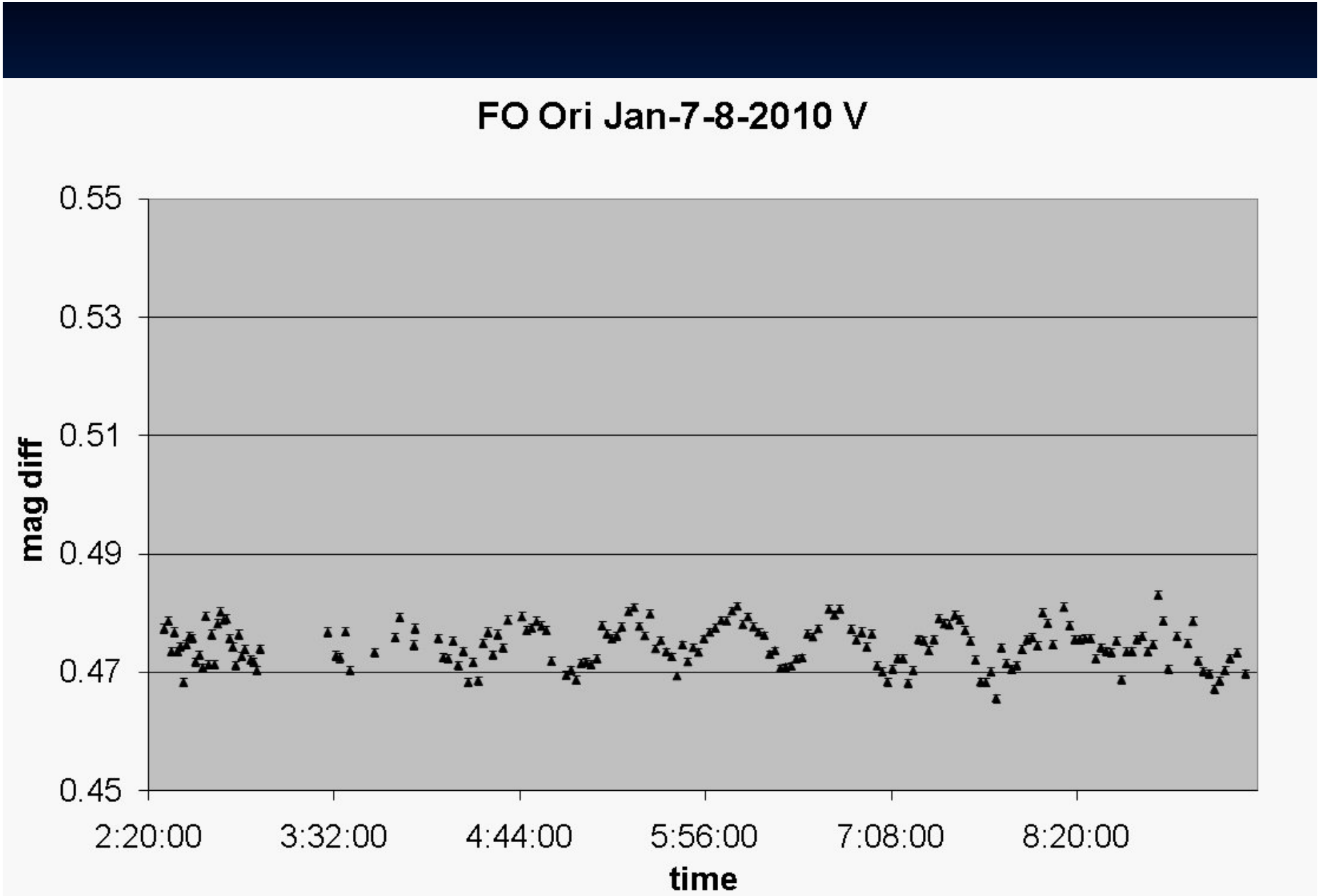
Name	Binary Period (days)	Binary Semi-Major (R_{Sun})	Coverage %	Min. Planet Radius (R_{Jup})	Max. Planet Period days)
FO ORI A	18.80	45.90	39.7	1.06	3.61
FO Ori B			34.8	1.79	3.27
V541 Cyg A	15.34	47.18	35.9	1.42	2.89
V541 Cyg B			34.1	1.42	2.72
DF Peg A	14.70	42.49	59.4	1.47	2.84
DF Peg B			52.8	1.35	0.98
BW Aqr A	6.72	20.6	93.8	0.72	0.95
BW Aqr B			93.3	0.80	0.90
HS Aur A	4.91	14.73	65.7	0.51	0.93
HS Aur B			61.3	0.54	0.86
WZ Oph A	4.18	14.32	92.0	1.01	0.78
WZ Oph B			92.2	1.00	0.75
BS Dra A	3.36	12.83	83.7	0.75	0.64
BS Dra B			78.1	0.50	0.59

The end is near…

- So far there has been no detections – but lots of false alarms.
- This program will end when the coverage reaches 90 % on the most promising targets.
- Longer period eclipsing systems are rare.

Unexpected results

1. The discovery of more than a half dozen new variable stars.
2. More than doubled the known number of δ-Scuti intrinsic variable stars in eclipsing binaries.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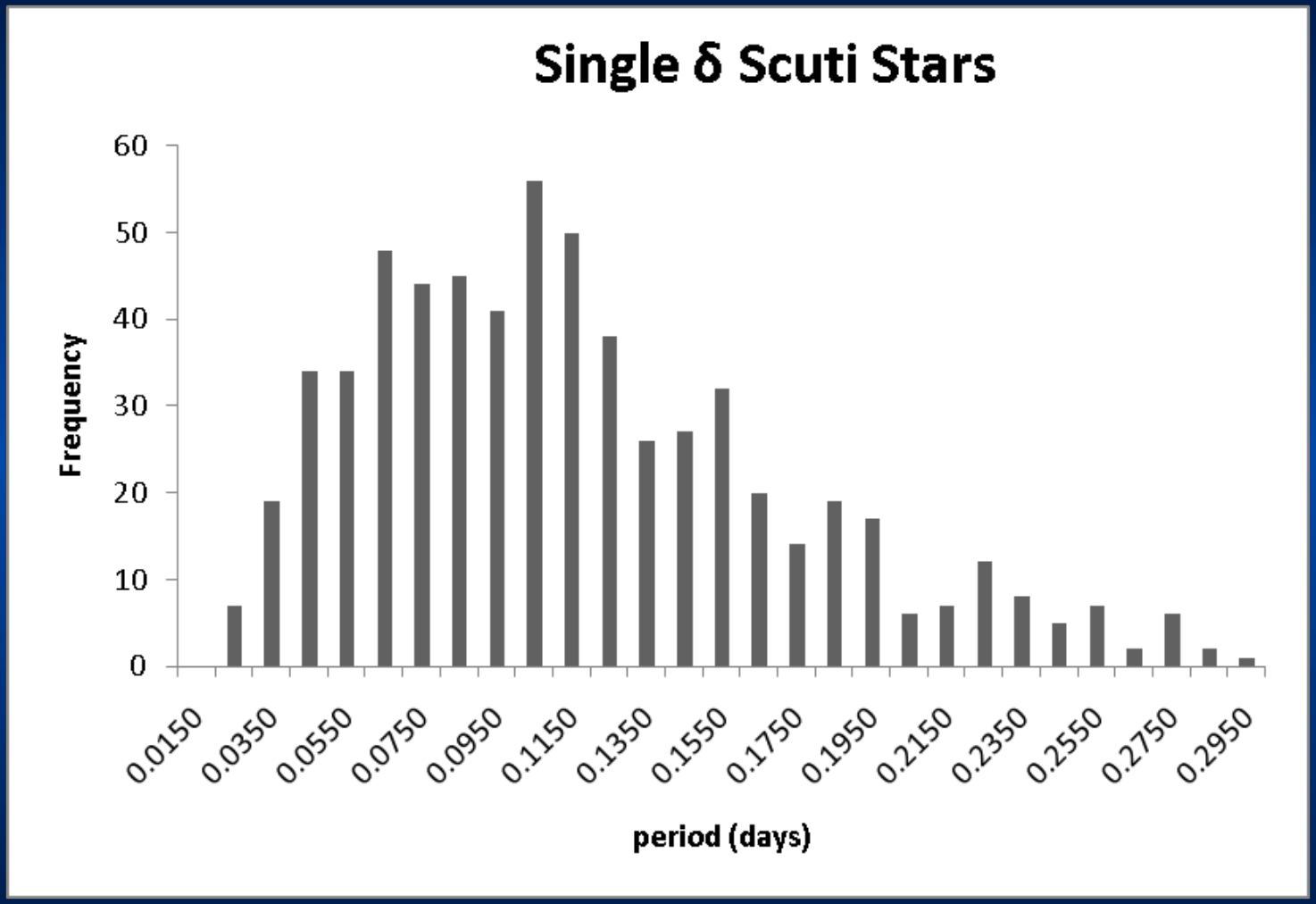
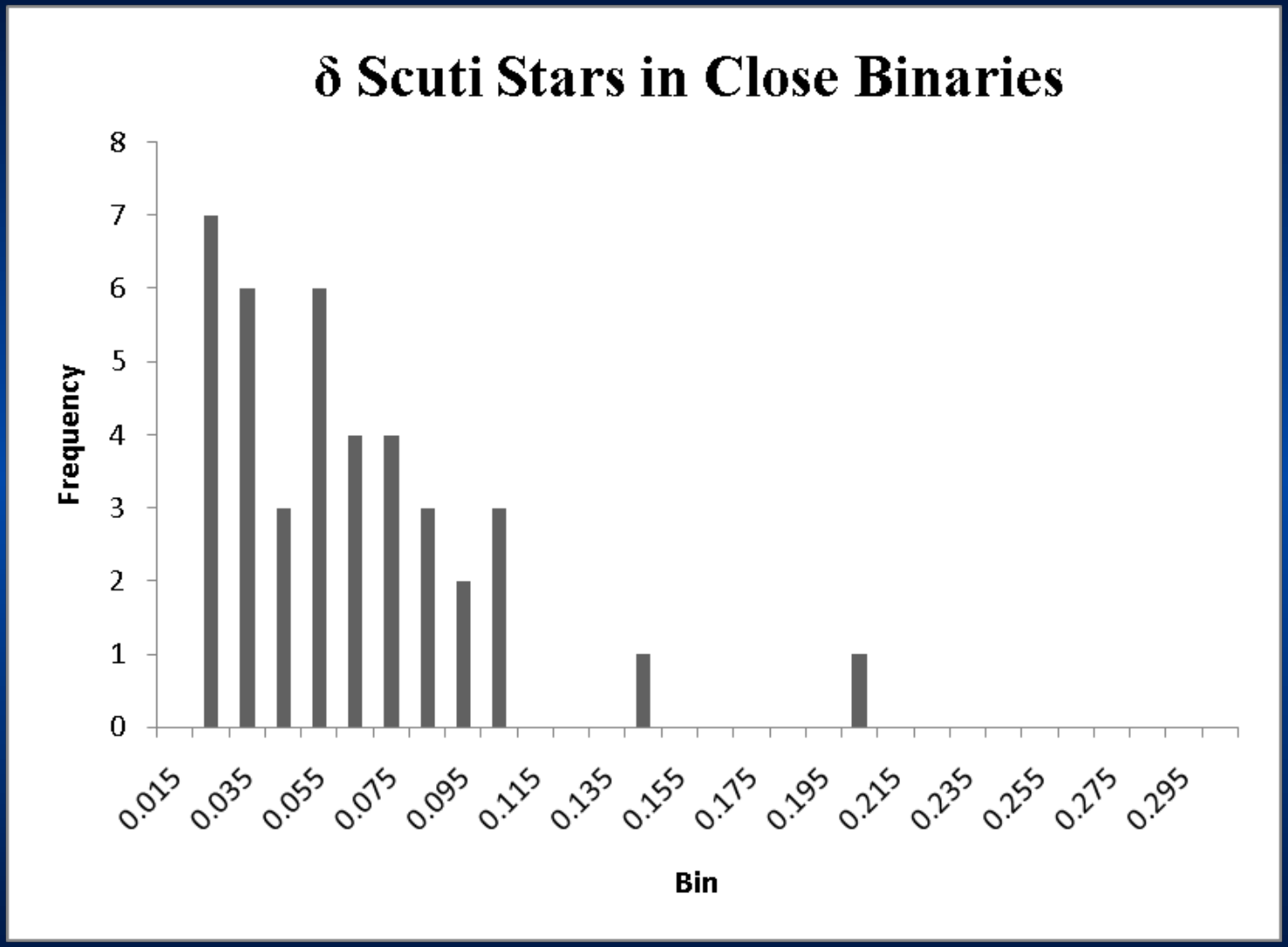
0.53
0.51
0.49
0.47
0.45
mag diff
2:20:00
3:32:00
4:44:00
5:56:00
7:08:00
8:20:00
time

Unexpected results

3. Confirm δ-Scuti stars pulsate faster in binary star systems.


Single δ Scuti Stars
Frequency
60
50
40
30
20
10
0
0.0150
0.0350
0.0550
0.0750
0.0950
0.1150
0.1350
0.1550
0.1750
0.1950
0.2150
0.2350
0.2550
0.2750
0.2950
period (days)


δ Scuti Stars in Close Binaries
Frequency
8
7
6
5
4
3
2
1
0
0.015
0.035
0.055
0.075
0.095
0.115
0.135
0.155
0.175
0.195
0.215
0.235
0.255
0.275
0.295
Bin