Porównanie dopasowania kilku liniowych efemeryd z modelem trzeciego ciała dla grupy gwiazd zaćmieniowych wykazujących duże zmiany O-C.

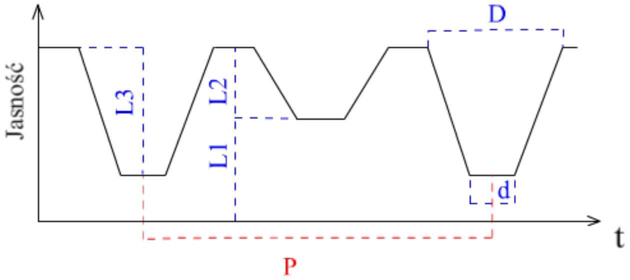
Damian Jabłeka

Obserwatorium Astronomiczne Uniwersytetu Jagiellońskiego

12 maja 2015

Binary system

Light Curve



P - Period.

Period

$P = const$ if not of following occur:

Period

$P = const$ if not of following occur:

- mass loss,

Period

$P = const$ if not of following occur:

- mass loss,
- mass exchange,

Period

$P = const$ if not of following occur:

- mass loss,
- mass exchange,
- shape changes

Period

$P = const$ if not of following occur:

- mass loss,
- mass exchange,
- shape changes
- pulsation.

Minima predictions

If we know:

- period P,

Minima predictions

If we know:

- period P,
- time of one particular minimum JD_0

Minima predictions

If we know:

- period P,
- time of one particular minimum JD_0

we can predict further minima:

Minima predictions

If we know:

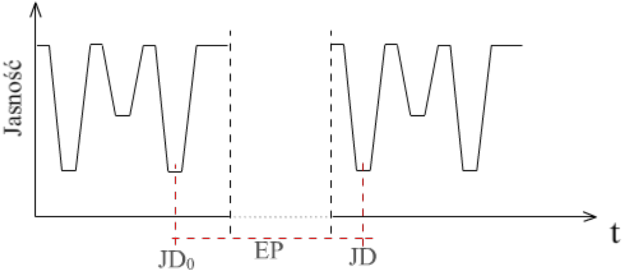
- period P,
- time of one particular minimum JD_0

we can predict further minima:

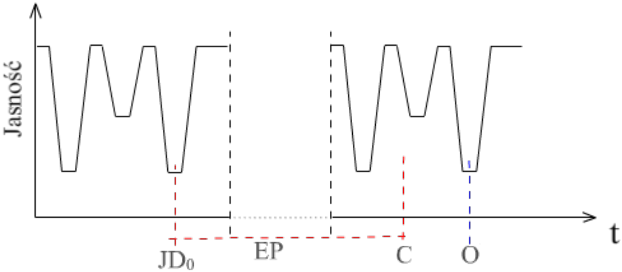
$$JD = JD_0 + EP$$

where:

$$E = floor\left(\frac{t - JD_0}{P}\right) + 1$$

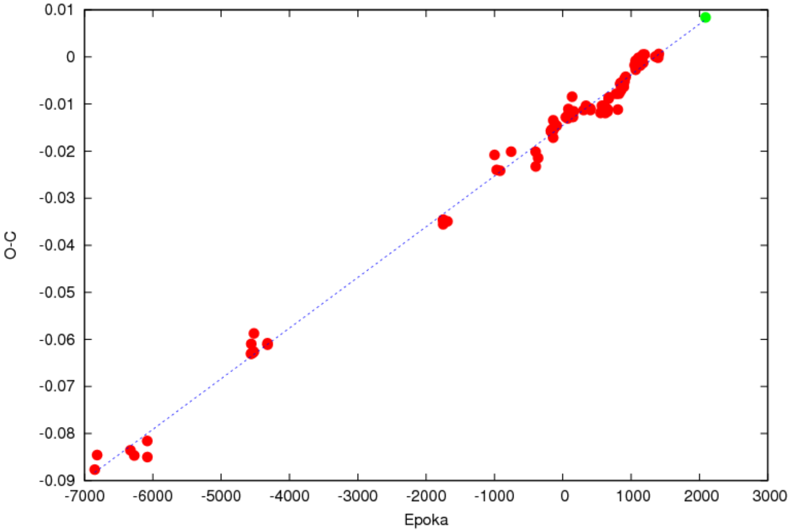


Sometimes we miss minimum.



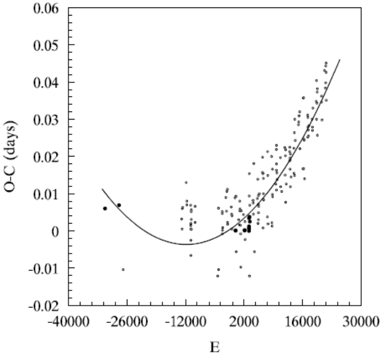
C - Calculation,
O - Observation.
To analyze difference we build O-C(E) diagrams

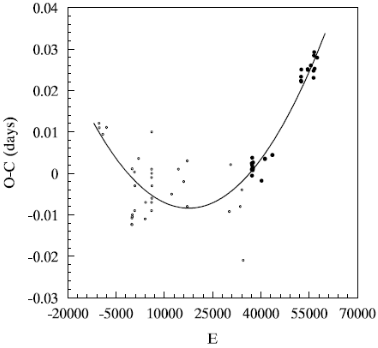
O-C types



Fittin (JD_0, P) - new exact ephemerides.

Typy O-C

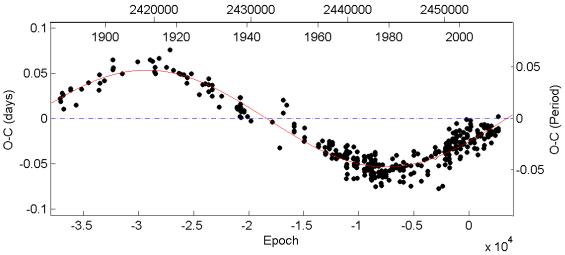




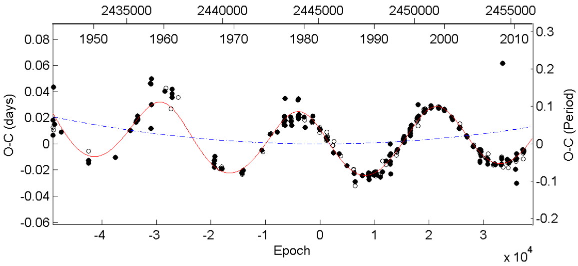
Fitting q

$O - C = JD - JD_0 - PE - qE^2.$

Typy O-C

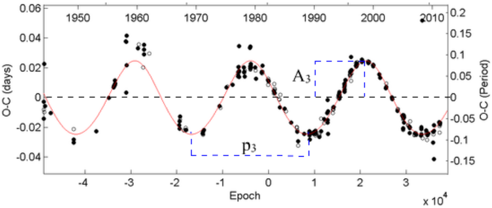


What can cause sine-like shape?



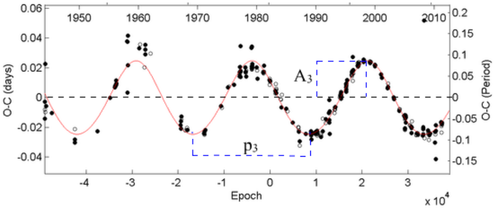
Light Time Effect

Light Time Effect



A_3 -semi amplitude,
c - speed of light,
a_{12} - semi-maior axis,
i - inclination.

Light Time Effect



A_3 -semi amplitude,
c - speed of light,
a_{12} - semi-maior axis,
i - inclination.

$$A_3 \cdot c = a_{12} \sin i$$

if orbit is circular, but generally is not

$$a_{12} \sin i = \frac{A_3 \cdot c}{\sqrt{1 - e^2 \cos^2 \omega}}$$

$$a_{12} \sin i = \frac{A_3 \cdot c}{\sqrt{1 - e^2 \cos^2 \omega}}$$

Knowing a_{12} and p_3 we can calculate mass function:

$$a_{12} \sin i = \frac{A_3 \cdot c}{\sqrt{1 - e^2 \cos^2 \omega}}$$

Knowing a_{12} and p_3 we can calculate mass function:

$$f(M_3) = \frac{(a_{12} \sin i)^3}{p_3^2}$$

$$a_{12} \sin i = \frac{A_3 \cdot c}{\sqrt{1 - e^2 \cos^2 \omega}}$$

Knowing a_{12} and p_3 we can calculate mass function:

$$f(M_3) = \frac{(a_{12} \sin i)^3}{p_3^2} = \frac{(M_3 \sin i)^3}{(M_1 + M_2 + M_3)^2}$$

Light Time Effect

$$a_{12} \sin i = \frac{A_3 \cdot c}{\sqrt{1 - e^2 \cos^2 \omega}}$$

Knowing a_{12} and p_3 we can calculate mass function:

$$f(M_3) = \frac{(a_{12} \sin i)^3}{p_3^2} = \frac{(M_3 \sin i)^3}{(M_1 + M_2 + M_3)^2} = \left[\frac{1}{p_3^2} \frac{A_3 \cdot c}{\sqrt{1 - e^2 \cos^2 \omega}} \right]^3$$

from this we can calculate lower mass limit $M_3 \sin i$

.

Light Time Effect

$$a_{12} \sin i = \frac{A_3 \cdot c}{\sqrt{1 - e^2 \cos^2 \omega}}$$

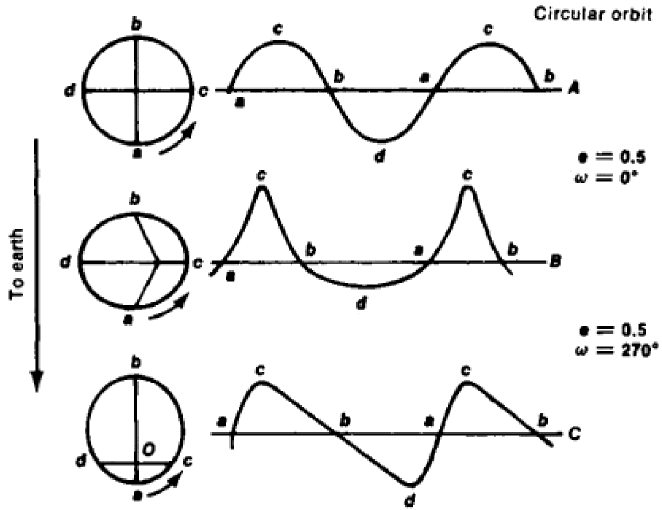
Knowing a_{12} and p_3 we can calculate mass function:

$$f(M_3) = \frac{(a_{12} \sin i)^3}{p_3^2} = \frac{(M_3 \sin i)^3}{(M_1 + M_2 + M_3)^2} = \left[\frac{1}{p_3^2} \frac{A_3 \cdot c}{\sqrt{1 - e^2 \cos^2 \omega}}\right]^3$$

from this we can calculate lower mass limit $M_3 \sin i$
. Limit - because of inclination i.

Light Time Effect

O-C changes with orbit shape



fitting LITE

Time of minimum delay:

$$\Delta\tau = \frac{A_3}{\sqrt{1 - e^2\cos^2\omega}} \cdot \left[\frac{1 - e^2}{1 + e\cos\nu}\sin(\nu + \omega) + e\sin\omega\right]$$

where ν true anomaly, $\nu = \nu(T_0, p_3)$.

fitting LITE

Time of minimum delay:

$$\Delta\tau = \frac{A_3}{\sqrt{1 - e^2\cos^2\omega}} \cdot \left[\frac{1 - e^2}{1 + e\cos\nu}\sin(\nu + \omega) + e\sin\omega\right]$$

where ν true anomaly, $\nu = \nu(T_0, p_3)$.

$O - C =$

fitting LITE

Time of minimum delay:

$$\Delta\tau = \frac{A_3}{\sqrt{1-e^2\cos^2\omega}} \cdot \left[\frac{1-e^2}{1+e\cos\nu}\sin(\nu+\omega) + e\sin\omega\right]$$

where ν true anomaly, $\nu = \nu(T_0, p_3)$.

$O - C = JD$

fitting LITE

Time of minimum delay:

$$\Delta\tau = \frac{A_3}{\sqrt{1 - e^2\cos^2\omega}} \cdot \left[\frac{1 - e^2}{1 + e\cos\nu}\sin(\nu + \omega) + e\sin\omega\right]$$

where ν true anomaly, $\nu = \nu(T_0, p_3)$.

$O - C = JD - JD_0$

fitting LITE

Time of minimum delay:

$$\Delta\tau = \frac{A_3}{\sqrt{1-e^2\cos^2\omega}} \cdot \left[\frac{1-e^2}{1+e\cos\nu}\sin(\nu+\omega) + e\sin\omega\right]$$

where ν true anomaly, $\nu = \nu(T_0, p_3)$.

$O - C = JD - JD_0 - P \cdot E$

fitting LITE

Time of minimum delay:

$$\Delta\tau = \frac{A_3}{\sqrt{1 - e^2\cos^2\omega}} \cdot \left[\frac{1 - e^2}{1 + e\cos\nu}\sin(\nu + \omega) + e\sin\omega\right]$$

where ν true anomaly, $\nu = \nu(T_0, p_3)$.

$$O - C = JD - JD_0 - P \cdot E - q \cdot E^2$$

fitting LITE

Time of minimum delay:

$$\Delta\tau = \frac{A_3}{\sqrt{1-e^2\cos^2\omega}} \cdot \left[\frac{1-e^2}{1+e\cos\nu}\sin(\nu+\omega) + e\sin\omega\right]$$

where ν true anomaly, $\nu = \nu(T_0, p_3)$.

$$O - C = JD - JD_0 - P \cdot E - q \cdot E^2 - \Delta\tau$$

Time of minimum delay:

$$\Delta\tau = \frac{A_3}{\sqrt{1 - e^2\cos^2\omega}} \cdot \left[\frac{1-e^2}{1+e\cos\nu}\sin(\nu+\omega) + e\sin\omega\right]$$

where ν true anomaly, $\nu = \nu(T_0, p_3)$.

$$O - C = JD - JD_0 - P\cdot E - q\cdot E^2 - \Delta\tau$$

Problem is classical inverse problem:

$$\{JD_i, \sigma_i\}_{i=1\ldots M} \rightarrow (JD_0, P, q, A, e, \omega, T_0, p_3)$$

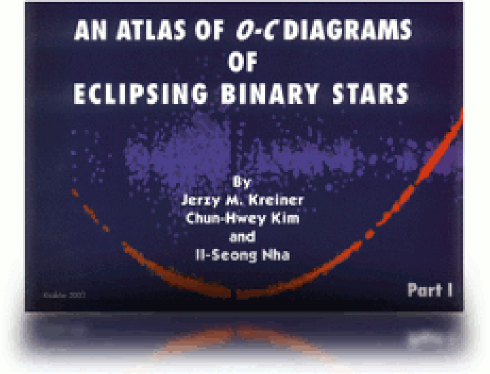
we can solve it minimising:

$$\chi^2_{LITE} = \sum_{i=1}^{M}\left(\frac{(O-C)_i}{\sigma_i}\right)^2$$

Using Monte Carlo Procedure.

Selection

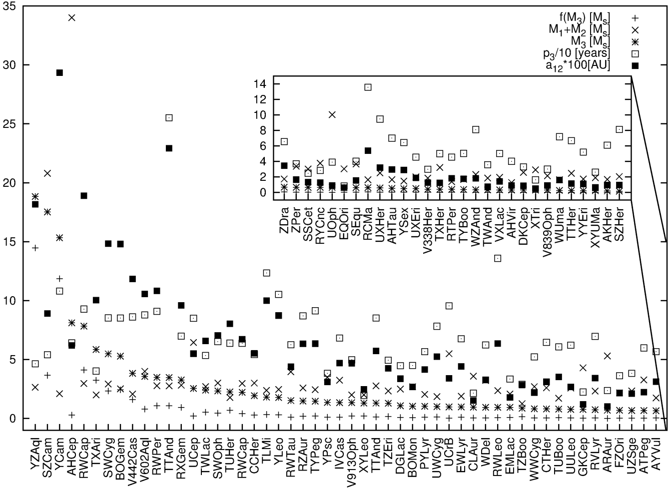
AN ATLAS OF O-C DIAGRAMS OF ECLIPSING BINARY STARS
Jerzy M. Kreiner
Chun-Hwey Kim, Il-Seong Nha



Out of 1140 O-C diagrams collected by Kreiner et al. we have chosen 79 binaries which exhibits possible cyclic orbital period variations.

Third body results - large sample

Preliminary results using Petr Zasche Matlab procedure.



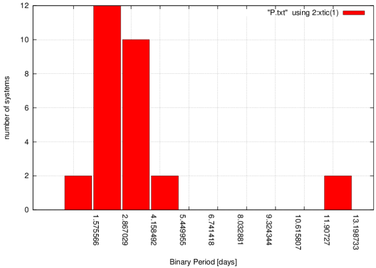
Third body results - selected sample

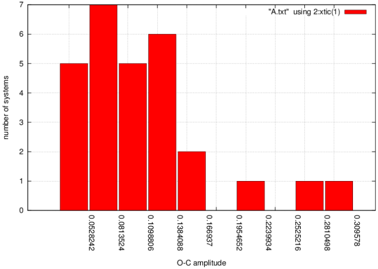
Based on preliminary results it turned out that 28 systems may have a third body, whose the lower mass limit exceeds that of a neutron star.

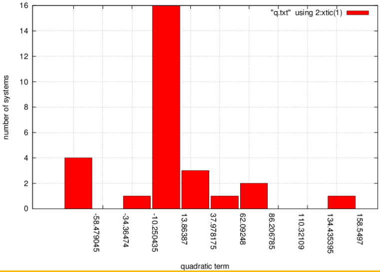
We use Monte Carlo fitting procedure.

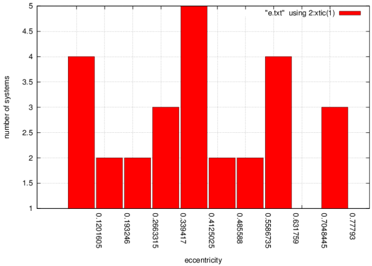
system	P_3 [years]	A [days]	e	$f(M_3)$ [$M_\odot$]	$M_3 \sin i$ [$M_\odot$]
AH Cep	70.52	0.07	0.53	0.31	7.52
BO Gem	84.32	0.16	0.24	2.91	5.91
CC Her	57.87	0.06	0.41	0.31	1.96
IV Cas	65.99	0.04	0.27	0.11	1.3
RW Cap	75.39	0.13	0.11	2.07	5.15
RW Per	85.14	0.11	0.27	1.13	3.57
RW Tau	65.65	0.04	0.48	0.11	1.28
RX Gem	69.23	0.1	0.3	1.16	3.65
RZ Aur	96.3	0.07	0.09	0.23	1.59
SW Cyg	78.99	0.13	0.22	1.81	4.74
SW Oph	78.98	0.1	0.6	1.38	4.12
SZ Cam	57.74	0.09	0.7	2.4	17.09
T Lmi	142.5	0.13	0.05	0.53	3.87
TT And	260.3	0.23	0.4	0.98	3.31
TU Her	64.21	0.08	0.37	0.73	2.3
TW Lac	75.84	0.07	0.48	0.33	1.93
TX Ari	41.57	0.11	0.44	4.82	7.66
TY Peg	130.14	0.08	0.64	0.27	1.65
TZ Eri	51.73	0.04	0.18	0.11	1.1
U Cep	131.39	0.28	0.12	6.31	13.67
V442 Cas	92.17	0.13	0.59	2.21	4.63
V602 Aql	115.32	0.14	0.73	1.13	4.26
V913 Oph	67.86	0.06	0.39	0.27	1.62
XY Leo	18.93	0.03	0.18	0.26	1.46
Y Cam	112.62	0.31	0.39	12.63	16.13
Y Leo	90.27	0.05	0.11	0.1	1.06
Y Psc	32.38	0.03	0.61	0.27	2.02
YZ Aql	45.4	0.2	0.52	20.36	24.92

Basic statistic

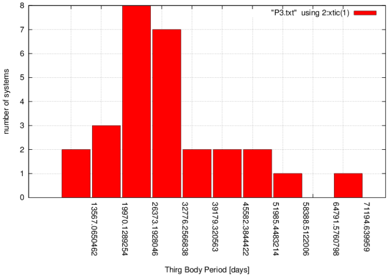


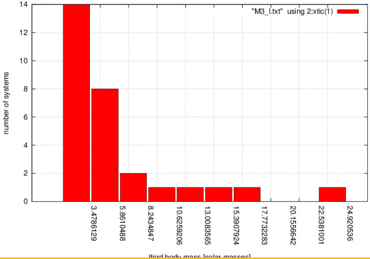


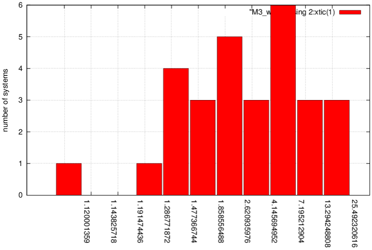




Basic statistic







Absolute parameters quality

system	ref.	P [days]	M_1 [$M_\odot$]	M_2 [$M_\odot$]	R_1 [$R_\odot$]	R_2 [$R_\odot$]
AH Cep	[6]	1.774738	15.8	13.7	6.3	5.8
BO Gem	[15]	4.068664	2.15	0.36	2.00	3.4
CC Her	[15]	1.734016	2.40	0.60	2.20	2.3
IV Cas	[7]	0.998515	1.98	0.81	2.13	1.8
RW Cap	[15]	3.392395	2.05	0.92	2.00	4.15
RW Per	[15]	13.198733	2.40	0.38	3.10	5.6
RW Tau	[12]	2.768831	2.55	0.55	2.25	3
RX Gem	[5]	12.208525	2.40	0.43	2.4	7.3
RZ Aur	[15]	3.010631	2.00	0.59	2.00	3.25
SW Cyg	[11]	4.573110	2.50	0.50	2.60	4.3
SW Oph	[15]	2.446005	2.40	0.60	2.20	2.85
SZ Cam	[10]	2.698464	16.6	11.9	9.4	5.4
T Lmi	[4]	3.019909	6.1	0.5	2.6	3.5
TT And	[15]	2.765109	2.15	0.62	2.00	3.1
TU Her	[15]	2.267031	1.27	0.51	1.40	2.6
TW Lac	[15]	3.037481	2.15	0.56	2.00	3.2
TX Ari	n.a.	2.691303	1.00	1.00	1.00	1
TY Peg	[15]	3.092222	2.15	0.30	2.35	2.6
TZ Eri	[2]	2.606101	1.97	0.37	1.69	2.6
U Cep	[3]	2.492911	4.30	2.15	3.10	4.50
V442 Cas	[15]	3.592201	1.75	0.32	1.80	3
V602 Aql	[15]	3.012500	2.15	1.85	2.00	1.85
V913 Oph	[14]	1.917343	1.9	0.45	1.9	2.25
XY Leo	[17]	0.284103	0.82	0.50	0.85	0.68
Y Cam	[13]	3.305570	1.70	0.41	2.95	3.07
Y Leo	[16]	1.686088	2.29	0.74	1.90	2.47
Y Psc	[11]	3.765833	2.80	0.70	3.06	3.98
YZ Aql	[15]	4.672488	2.05	0.60	2.00	4.4

[15] M. A. Svechnikov and E. F. Kuznetsova., 1990.

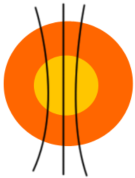
Alternative sine-like shape solution

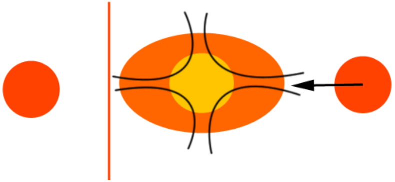
Orbital period - chromospherically activity coupling. Applegate 1992

Gravitational potential: $\Phi = -\frac{GM}{r} + \frac{1}{2} G Q_{ik} \frac{x^i x^k}{r^5}$

Quadrupole tensor: $Q_{ik} = 3J_i k - \delta_{ik} TrJ$

Inertia tensor: $J_{ik} = \int dm x_i x_k = \int d^3 x \varrho(x) x_i x_k$





Period changes: $\frac{\Delta P}{P} = -9 \left(\frac{R}{a}\right)^2 \frac{\Delta Q}{MR^2}$

Luminosity Variations: $\Delta L_{RMS} = \pi \frac{\Delta E}{P_{mod}}$

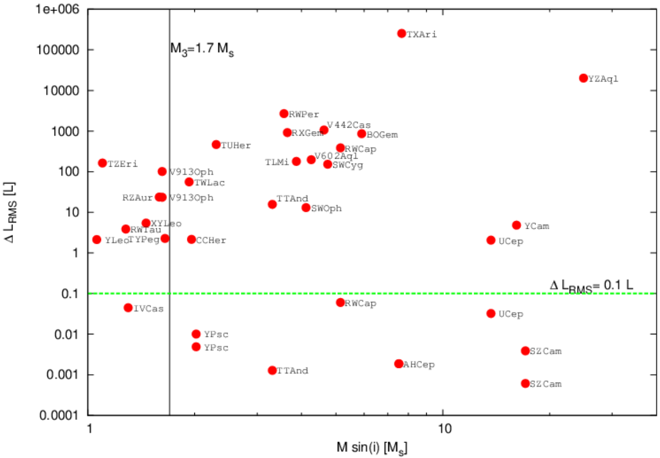
Magnetic field: $B^2 = 10 \frac{GM^2}{R^4} \left(\frac{a}{R}\right)^2 \frac{\Delta P}{P_{mod}}$

Applegate theory results

system	$B[kG]$	$\Delta L_{RMS}[L]$
AH Cep	13.45	0.002
BO Gem	85.35	860.350
CC Her	24.83	2.152
IV Cas	8.89	0.045
RW Cap	3.58	0.060
	71.34	385.482
RW Per	87.88	2686.380
RW Tau	33.31	3.881
RX Gem	64.33	916.013
RZ Aur	34.02	23.666
SW Cyg	53.18	151.960
SW Oph	35.64	13.043
SZ Cam	16.66	0.004
	9.78	0.001
T Lmi	57.47	178.985
TT And	33.65	0.001
	33.65	15.679

system	$B[kG]$	$\Delta L_{RMS}[L]$
TU Her	63.55	466.465
TW Lac	46.81	55.943
TX Ari	304.24	252926.100
TY Peg	17.63	2.272
TZ Eri	60.95	163.624
U Cep	4.94	0.032
	30.22	2.062
V442 Cas	64.38	1062.630
V602 Aql	53.26	196.993
	48.99	100.926
V913 Oph	27.03	23.506
XY Leo	27.79	5.422
Y Cam	16.42	4.819
Y Leo	21.97	2.137
Y Psc	4.13	0.010
	36.37	0.005
YZ Aql	204.31	20074.710

LTTE-Applegate comparision

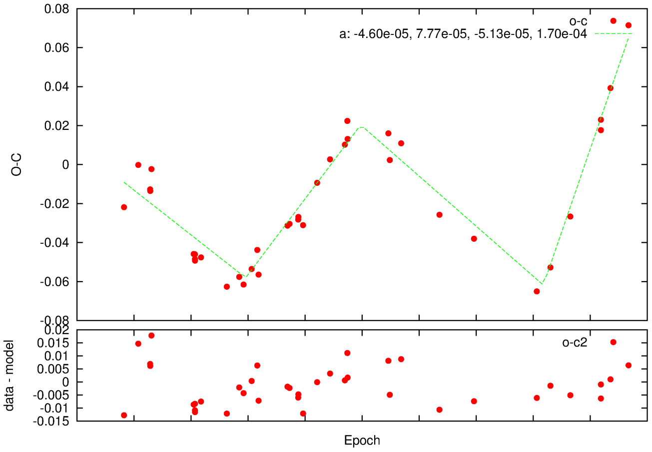


Spectral type

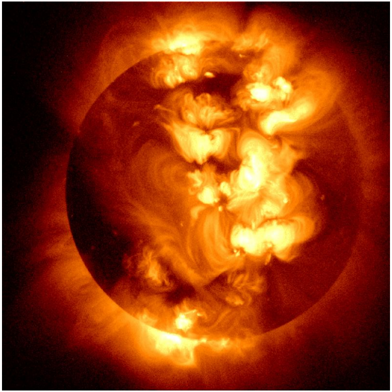
According to Applegate (1992), Lanza (2006) spectral type of at least one component > F3

system	1.	2.	ref.
Ah Cep	B0.5 Vn	B0.5 Vn	2005AJ....129..990K
SZ Cam	O9.5V	B5V	1975Ap%26SS..36..329B
V602 Aql	A2	A5	SK
IV Cas	A3V	early-K	2010PASP..122.1311K
RW Tau	B8V	K0 IV	1983ApJ...272..206P
RX Gem	A0	K2	1987PASP...99..274D
SW Cyg	A2e	K0	1980A% 26AS...39..265M
T Lmi	A0	G5III	1979A% 26AS...36..273C
TZ Eri	A56 V	K01 III	aasabs199818ds7638ds7638.html
U Cep	B8V	G8 III-IV	1986Ap% 26SS.125..219K
XY Leo	K0	K0	2006PASA...23..154D
Y Cam	A9IV	K1IV	2010MNRAS.408.2149R
Y Leo	A3	K0	1980IBVS.1786....1G
Y Psc	K3	K0	1980A% 26AS...39..265M
BO Gem	A2	K3IV	SK
CC Her	A0	G6IV	SK
RW Cap	A3	G3IV	SK
RW Per	A5IVE	G9IV	SK
RZ Aur	A3	K0IV	SK
SW Oph	A0	G7IV	SK
TT And	A2	G7IV	SK
TU Her	F5	M1IV	SK
TW Lac	A2	K0IV	SK
TY Peg	A2	G6IV	SK
V442 Cas	A7	K2IV	SK
YZ Aql	A3	K5IV	SK
V913 Oph	?	?	?
TX Ari	?	?	?

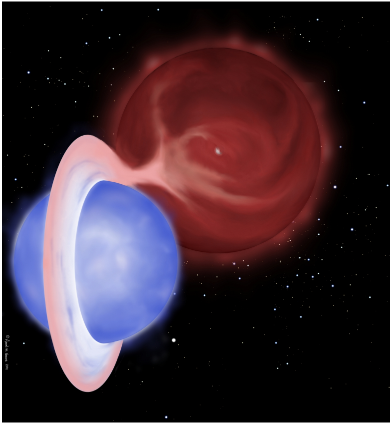
Is sine really sine



Mass loss



Mass exchange



What can cause such rapid changes

Following Tout and Hall (1991), the relationship between the rate of period change and the rates of mass and angular momentum loss of the binary can be written as

$$\frac{\dot{P}}{P} = -2\frac{\dot{M}}{M} - \frac{3(M_2 - M_1)}{M_1 M_2}\dot{M}_2 + 3K$$

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FLE results

system	DM_1 $10^{-7} M_\odot$	DM_2 $10^{-7} M_\odot$	DM_3 $10^{-7} M_\odot$	DM_4 $10^{-7} M_\odot$	DM_5 $10^{-7} M_\odot$
RWTau	-12.5	96.9	-34.7	-45.7	84.9
AhCep	184.0	-2100.0	1340.0		
CFTuc	-7.4	203.0	-278.0		
IVCas	7.1	-71.6	62.2		
SWCyg	10.8	-125.0	115.0		
TLmi	-2.8	32.7	26.5		
TWLac	-0.8	84.9	-124.0		
YCam	14.4	-99.4	-126.0		
YZAql	-38.4	264.0	-317.0		
BOGem	5.9	-113.0			
CCHer	8.7	-81.5			
RWCap	-18.6	218.0			
RWPer	7.3	-76.7			
RXGem	7.2	-62.2			
RZAur	-6.7	71.8			
SWOph	-15.3	146.0			
SZCam	-129.0	1270.0			
TTAnd	-2.2	79.0			
TUHer	9.4	-111.0			
TXAri	6.2	-119.0			
TYPeg	-3.3	37.2			
TZEri	3.3	-48.1			
UCep	120.0	-379.0			
V602Aql	8.7	-235.0			
V913Oph	9.2	-86.6			
YLeo	10.9	-80.9			
V442Cas	7.7				

Is any solution better

LTTE

- 6 free parameters
- clear theory
- complex theory
- non separated parameters

FLE

- 4-10 free parameters
- not fully explained
- simple fit
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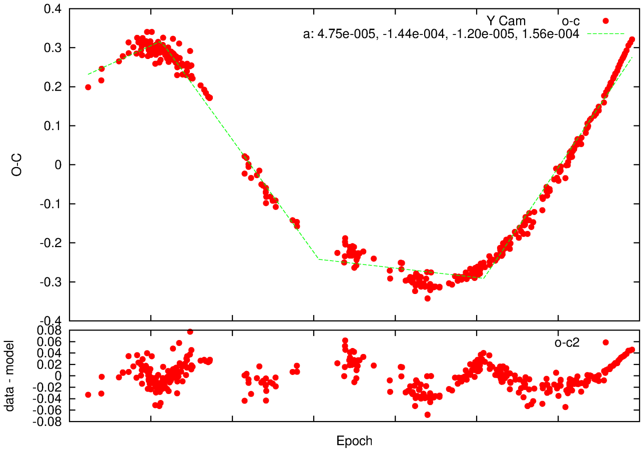
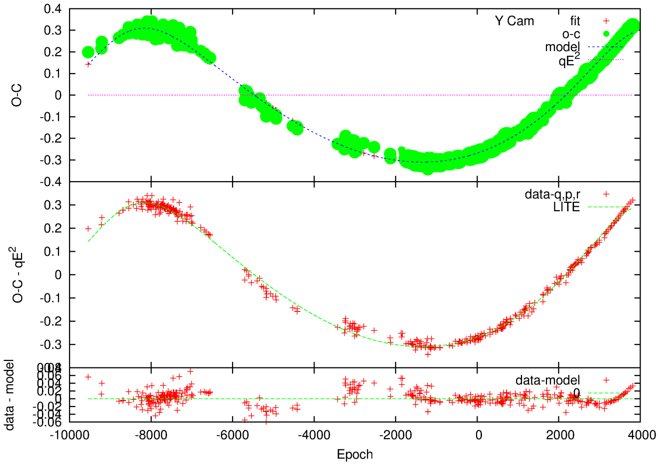
We can compare fit quality in terms of sum of squares of residua.

Y Cam FLE

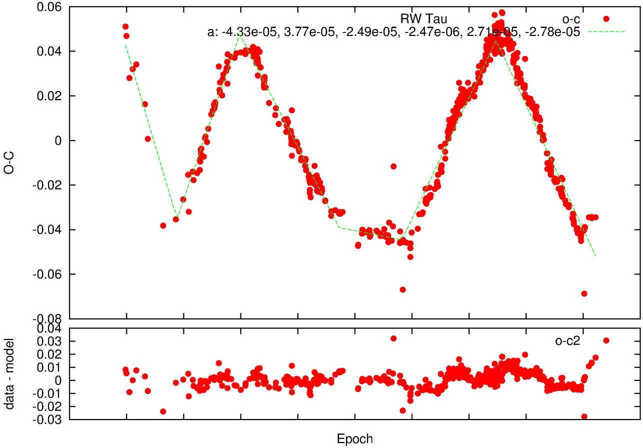


Y Cam
o-c
a: 4.75e-005, -1.44e-004, -1.20e-005, 1.56e-004
O-C
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
o-c2
data - model
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
Epoch

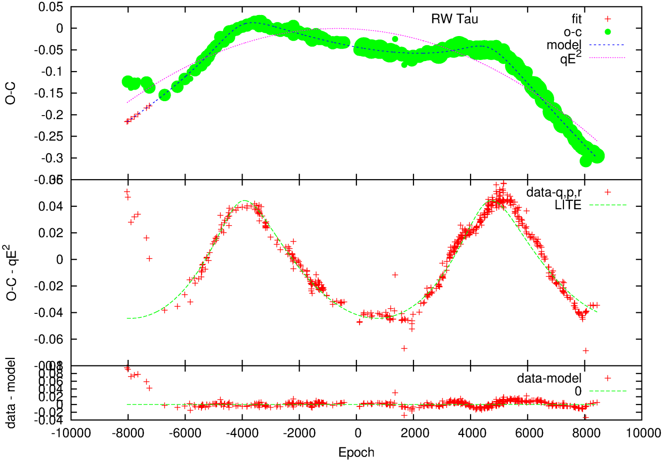
Y Cam LTTE


Y Cam
fit
o-c
model
qE2
O-C
data-q,p,r
LITE
O-C - qE2
data-model
0
data - model
Epoch

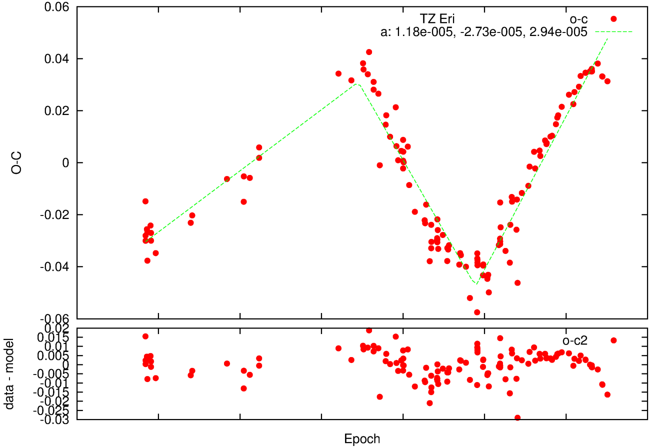
RW Tau FLE



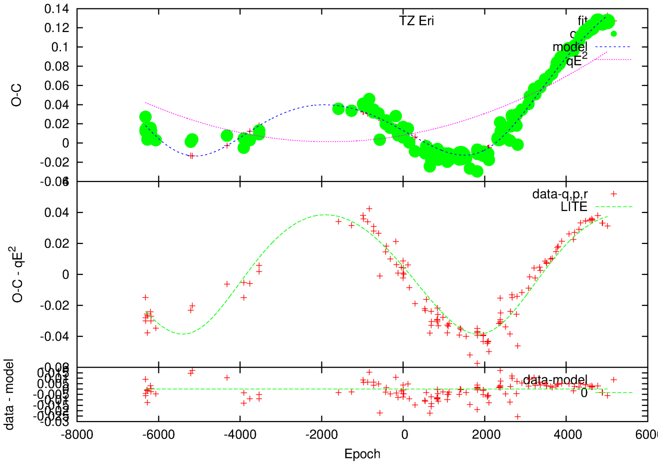
RW Tau
o-c
a: -4.33e-05, 3.77e-05, -2.49e-05, -2.47e-06, 2.71e-05, -2.78e-05
O-C
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
o-c2
data - model
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
Epoch


RW Tau
fit
o-c
model
qE^2
data-q,p,r
LITE
data-model
0
O-C
O-C - qE^2
data - model
Epoch
-10000
-8000
-6000
-4000
-2000
0
2000
4000
6000
8000
10000

TZ Eri FLE

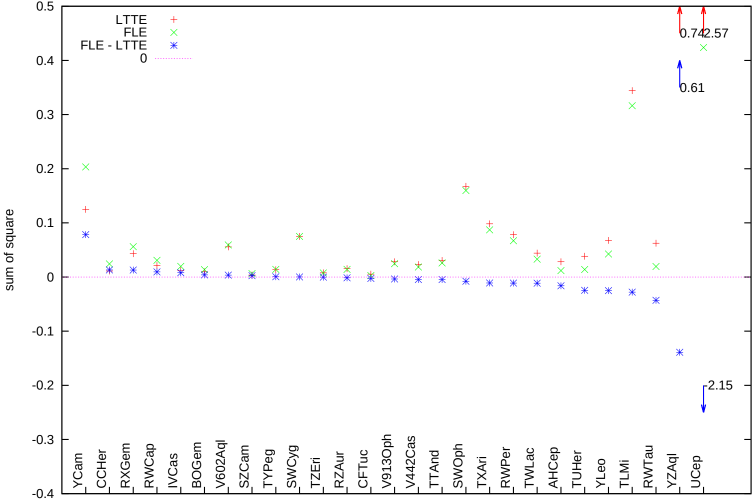

TZ Eri
o-c
a: 1.18e-005, -2.73e-005, 2.94e-005
O-C
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
o-c2
data - model
0.02
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02
-0.025
-0.03
Epoch

TZ Eri LTTE



TZ Eri
fit
O-C
model
qE2
O-C - qE2
data-q,p,r
LITE
data - model
data-model
0
Epoch

Fit quality comparison



Conclusion

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- In FLE idea more problematic is that we need mechanism of accretion matter onto the system from surrounding space.
- Fit quality can also be caused by very uneven data coverage, which can favor linear fit rather than sine-like one.

Confirmation

We use Robo-AO, the first robotic laser adaptive system at the Palomar 60-inch telescope to direct imaging of additional components in binary systems.

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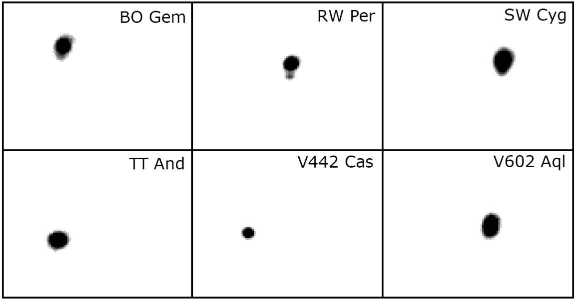

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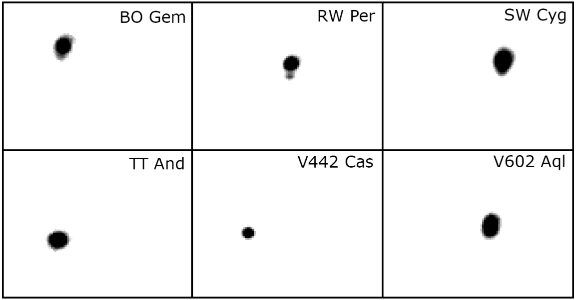
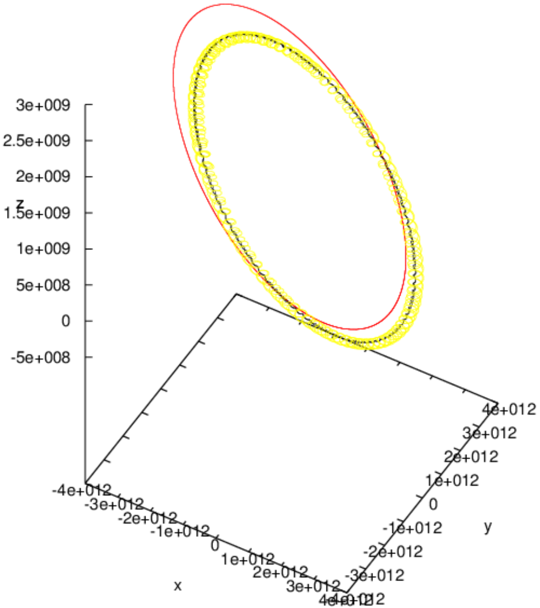


The RW Per parallax from the Hipparcos catalogue equals to $3.28 mas$ gives us distance from binary to third component $(52.39 \pm 3.14) au$. On the other hand, we can calculate the distance from the third body fitting. The O-C amplitude equal to $0.11 days$ corresponds to the distance of $(19.52 \pm 5.68) au$.

Dynamic three body simulations



Dziękuję za uwagę!

jableka@oa.uj.edu.pl