Orbit determination of eclipsing binary asteroids from photometry

Petr Scheirich, Petr Pravec

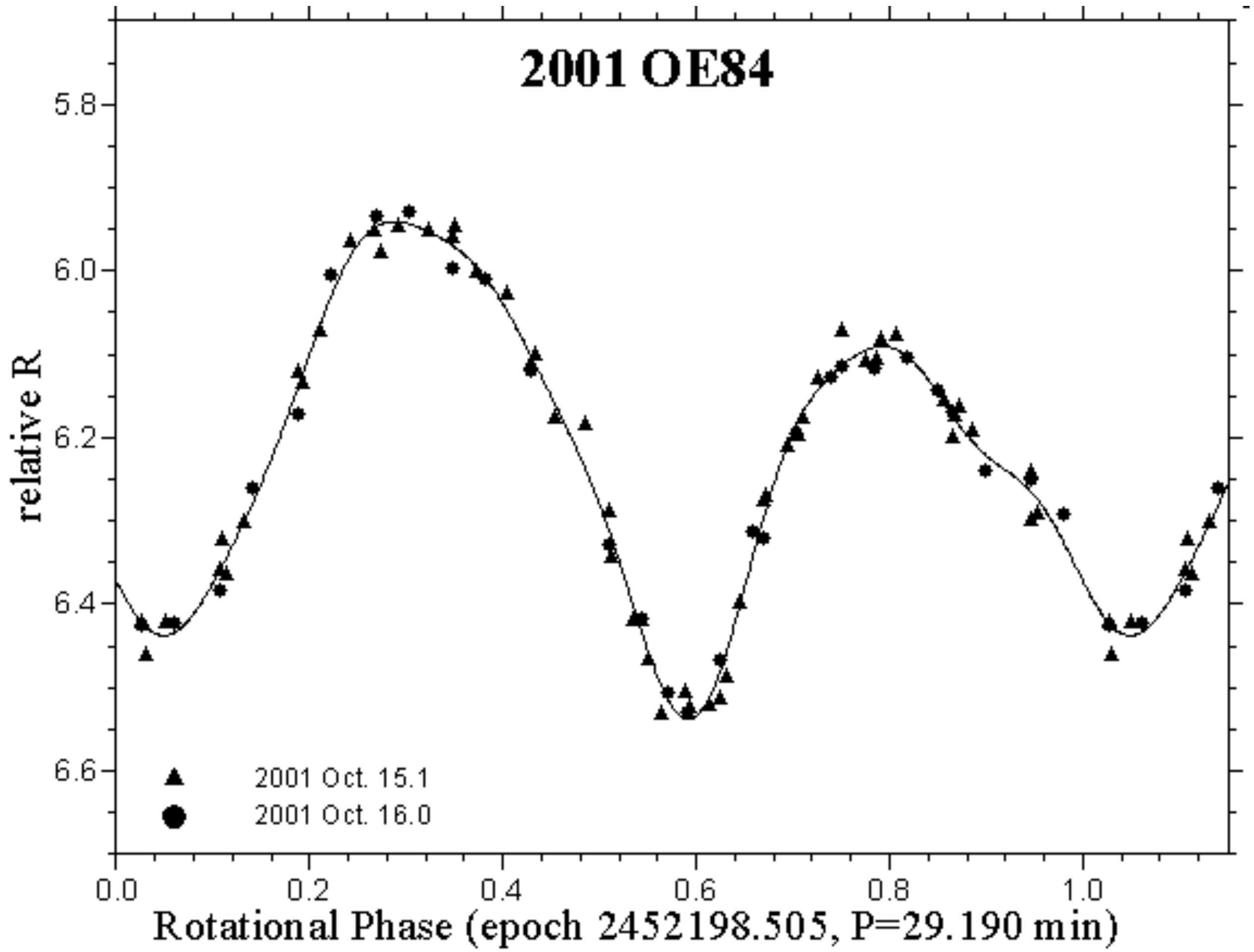
Ondrejov obs., Czech Republic

and many observers

Orbiting couples: "pas de deux" in the Solar System and the Milky Way

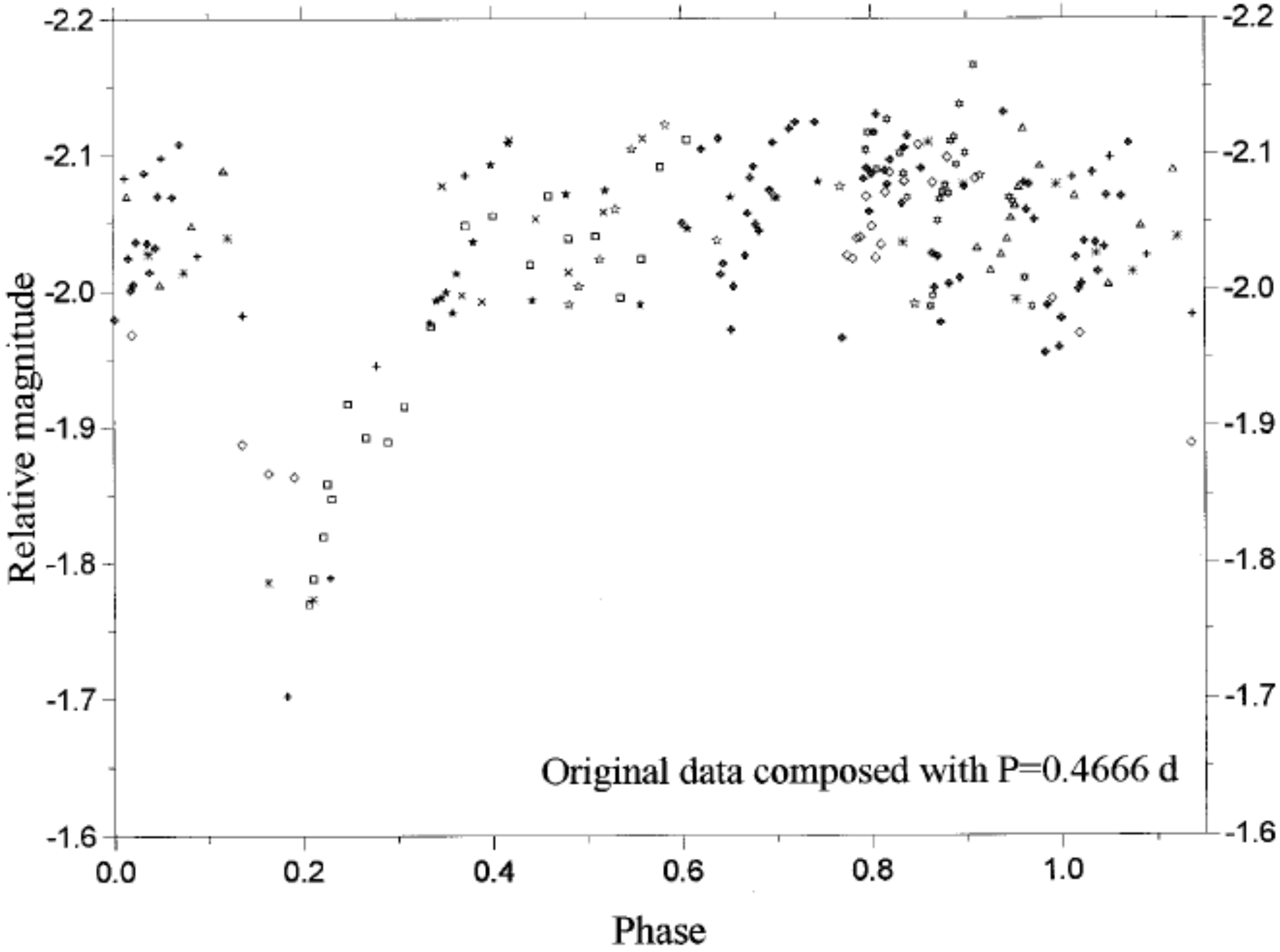
Paris, October 10-12, 2011

Lightcurve of ordinary asteroid



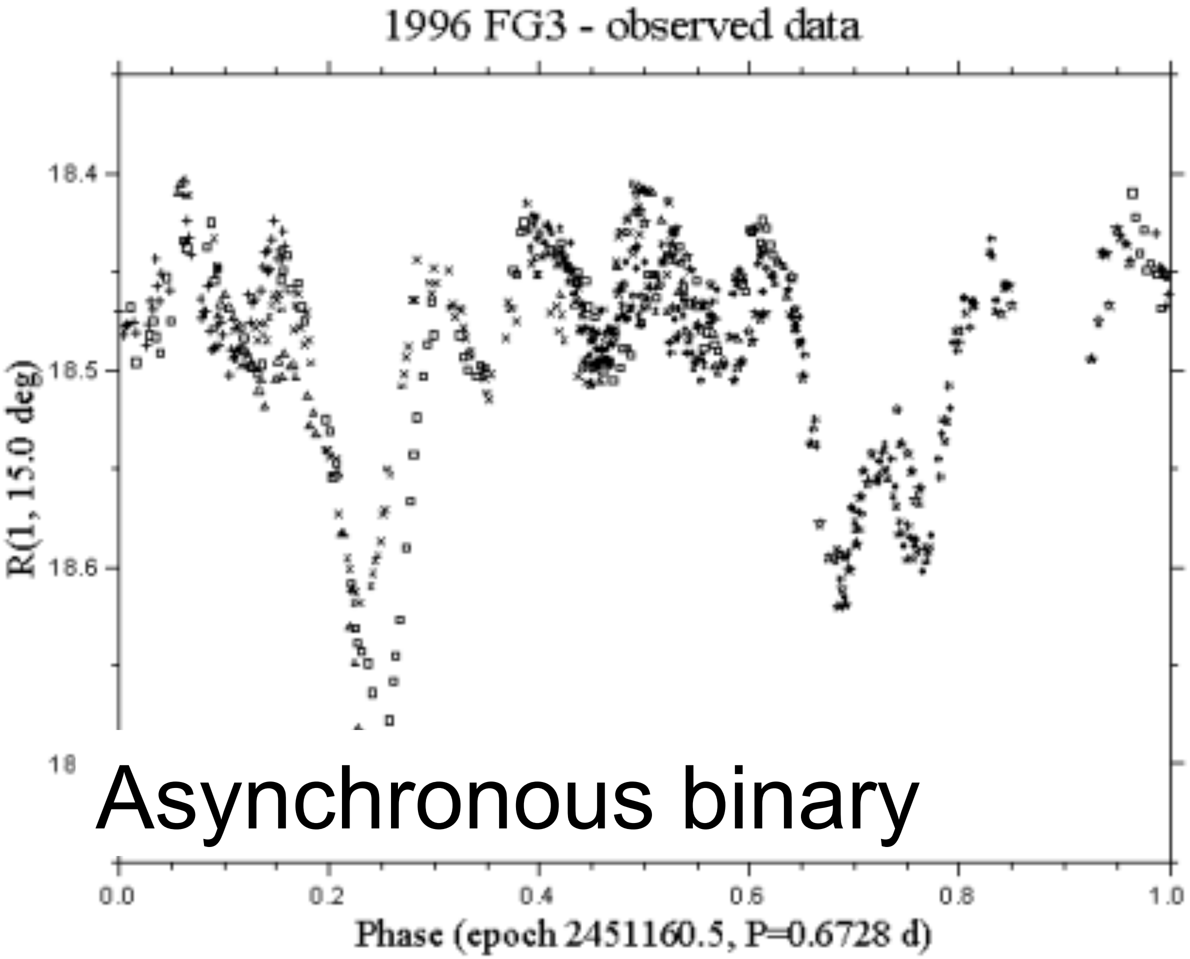
First binaries resolved from photometry

1994 AW_1 (Pravec and Hahn, 1997)

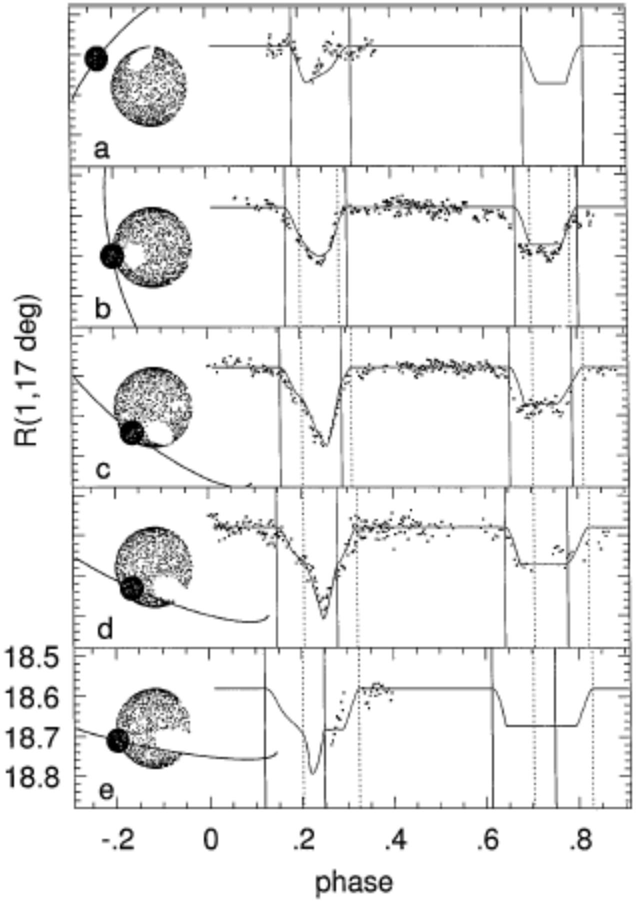


First binaries resolved from photometry

1996 FG_3 (Pravec et al, 2000)



Asynchronous binary



Models of binaries derived from photometry

- 10 NEA binaries (22 oppositions)
- 15 MBA binaries (33 oppositions)

Where all the data come from?

O

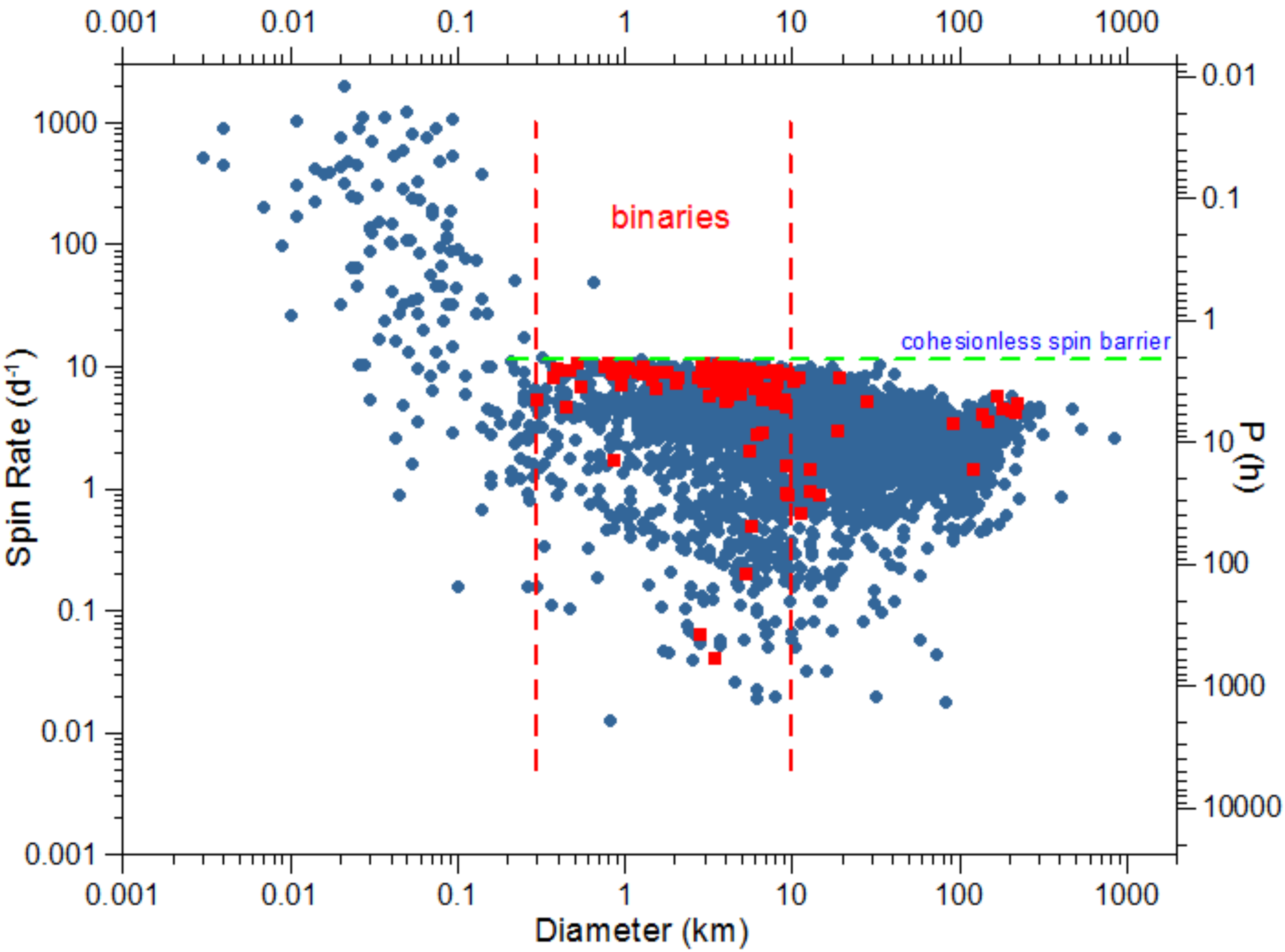
ecli

Orbiting coup

1	Ondřejov Observatory, Czech Republic	0.65	P. Kušnirák, L. Šarounová, P. Pravec, M. Wolf
2	European Southern Observatory, Chile	0.6	S. Mottola, G. Hahn
3	Kharkiv Observatory, Ukraine	0.7	Yu. Krugly, F. Velichko
4	Elginfield Observatory, Ontario, Canada	1.2	P. Brown, G. Esquerdo, Z. Krzeminski, N. Kaiser
5	Table Mountain Observatory, California	0.6	M. Hicks
6	Carbuncle Hill Observatory, Rhode Island	0.35	D. Pray
7	Palmer Divide Observatory, Colorado	0.5	B. Warner
8	River Oaks Observatory, Texas	0.41	W. Holliday
9	Modra Observatory, Slovakia	0.6	A. Galád, Š. Gajdoš, J. Világi
10	Badlands Observatory, South Dakota	0.66	R. Dyvig, V. Reddy, K. Kirsch
11	Stull Observatory, New York	0.82	D. DeGraff
12	Mauna Kea, Hawaii	2.2	D. Tholen, R. Whiteley
13	Steward Observatory, Arizona	1.5	A. Grauer, S. Larson
14	MacLean Observatory, California	0.55	R. Stephens, L. Snyder
15	Baton Rouge Observatory, Louisiana	0.5	W. Cooney
16	Xinglong St., Beijing Observatory, China	0.6	H. Yan, J. Zhu
17	Lick Observatory, California	3.0	F. Marchis
18	La Palma Observatory, Canary Islands	1.2	M. Grenon, G. Burki
19	Hunters Hill Observatory, Australia	0.25	D. Higgins
20	Whitin Observatory, Massachusetts	0.61	G. Funkhouser, B. Knight, S. Slivan
21	Blauvac Observatory, France	0.31	R. Roy
22	Village-Neuf Observatory, France	0.25	C. Demeautis, D. Matter
23	F.-X. Bagnoud Observatory, Switzerland	0.6	N. Waelchli, Y. Revaz, R. Behrend
24	Guitalens, France	0.20	A. Klotz, M. Rieugné, P. Thierry
25	Saint-Hélène Observatory, France	0.20	V. Cotrez, C. Demeautis, R. Behrend
26	Antibes Observatory, France	0.25	L. Brunetto, G. Kober

2006

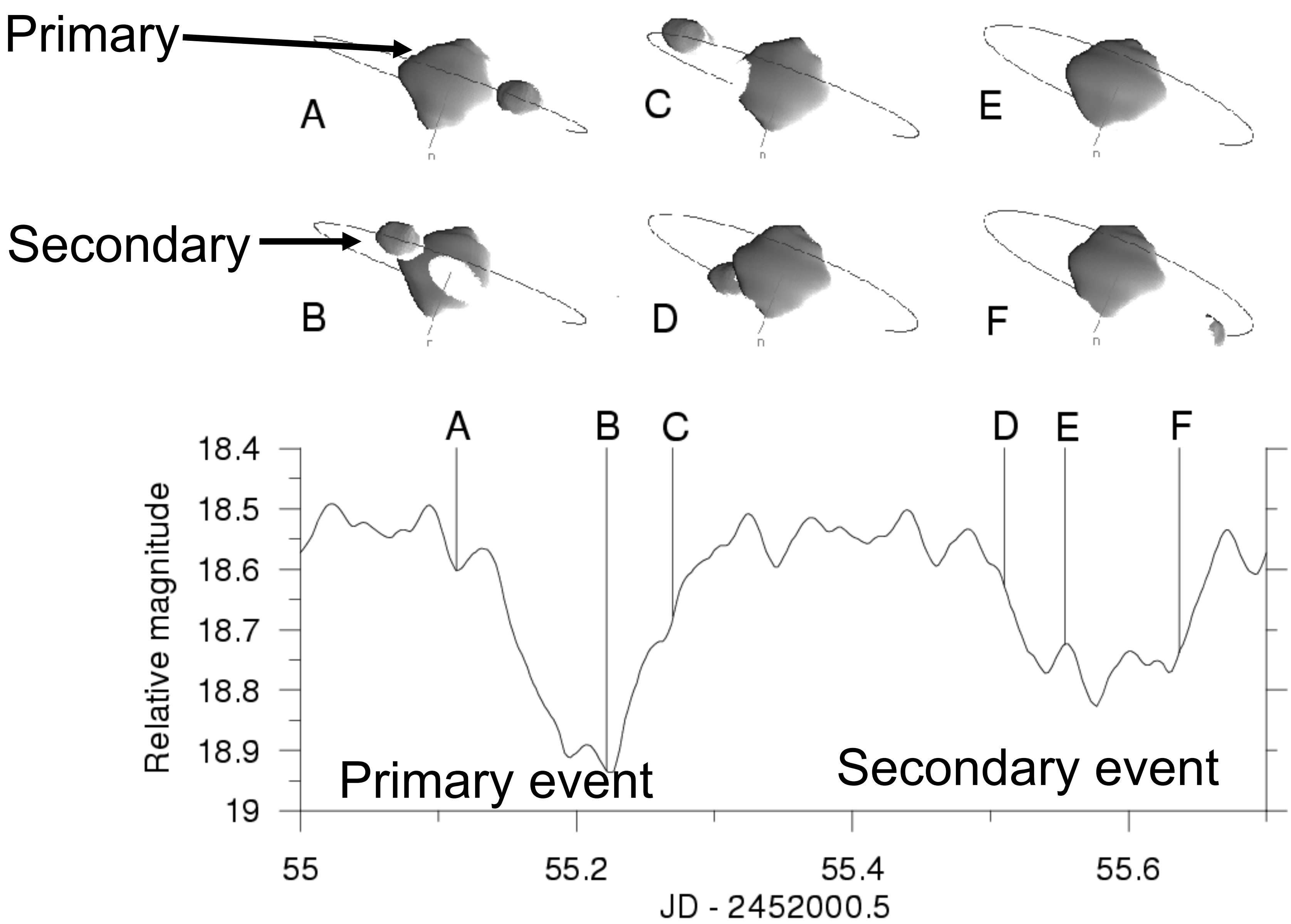
Why to do photometry of binaries?



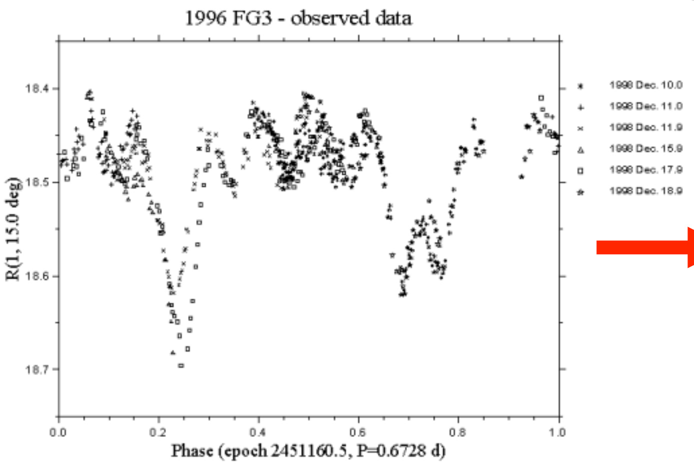
Why to do photometry of binaries?

- poles distribution
- dynamical evolution

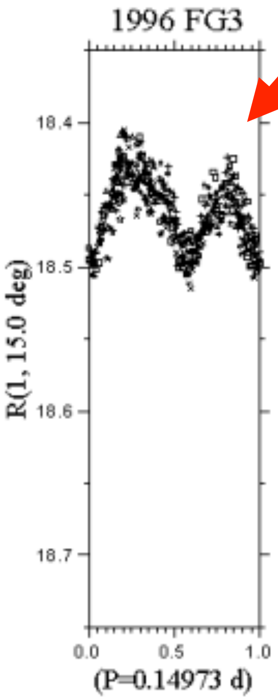
Lightcurve of binary asteroid

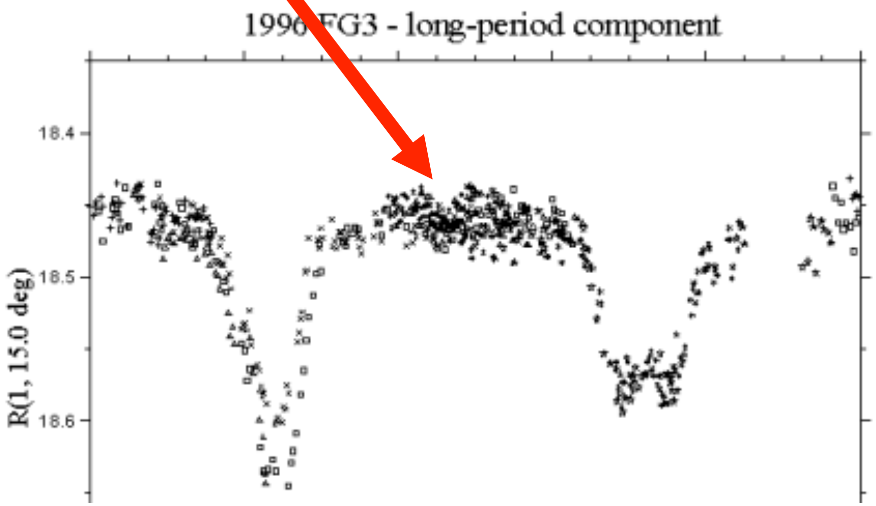


Long-period component extraction



$$F(t) = C_0 + \sum_{j=1}^{m} \left[C_{j0} \cos \frac{2\pi j}{P_1}(t - t_0) + S_{j0} \sin \frac{2\pi j}{P_1}(t - t_0) \right] + \sum_{k=1}^{m} \left[C_{0k} \cos \frac{2\pi k}{P_2}(t - t_0) + S_{0k} \sin \frac{2\pi k}{P_2}(t - t_0) \right]$$



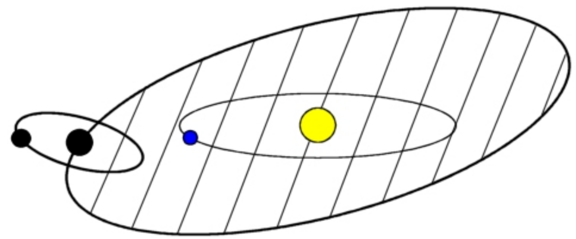


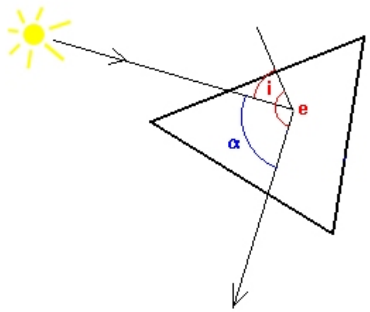
L.p. component = mutual events + rotation of secondary

(The long period component of) Lightcurve simulation – the direct problem

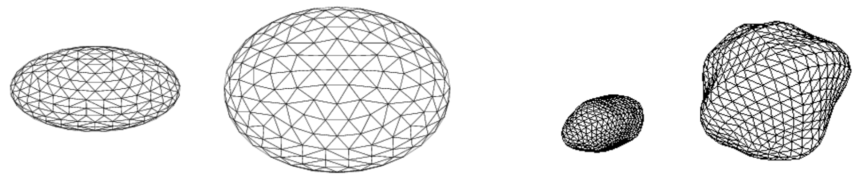
Input parameters:

- Heliocentric orbit → geometry
- Keplerian elements of mutual orbit (circular, eccentric)
- Shape and size ratio of components
- Scattering law





Two-axis ellipsoids or any arbitrary shape approximated by polyhedra with triangular facets



The lightcurve of the system is computed using simple ray-traycing code.

The inverse problem

Fitted parameters:

- Keplerian elements of mutual orbit:
  - a/A_p – semimajor axis
  - l_P – ecl. longitude of orbit's pole
  - b_P – ecl. latitude of orbit's pole
  - P_{orb} – sidereal orbital period
  - L_0 – mean length of secondary at given epoch
  - e – eccentricity
  - w – argument of pericenter
- Shape and size ratio of components:
  - flattening of primary A_p/C_p,
  - elongation of secondary A_s/C_s,
  - size ratio of both bodies A_s/A_p

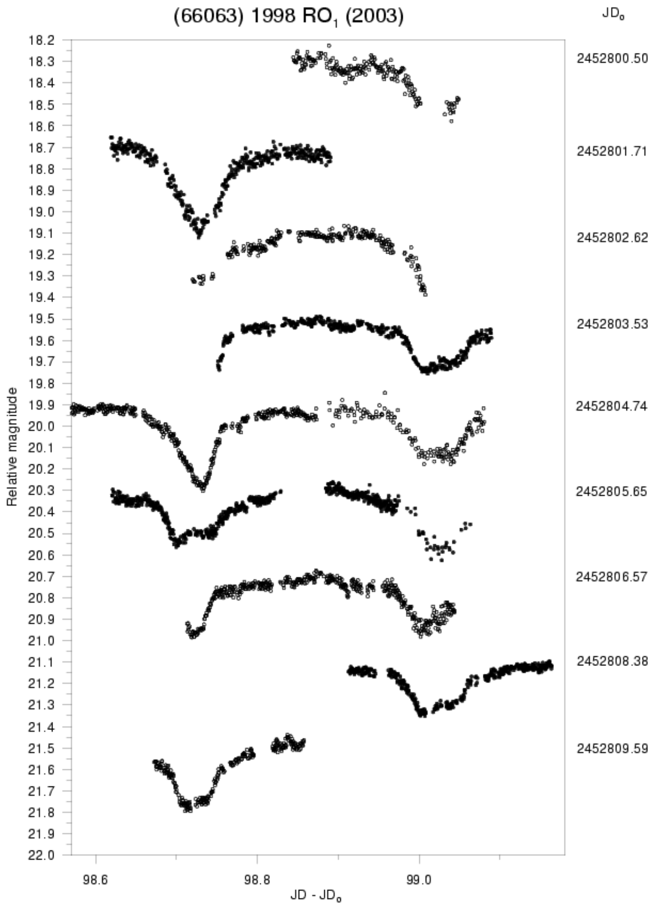
Pre-estimates of initial parameters

- Synodic orbital period

$$F(t) = C_0 + \sum_{j=1}^{m}\left[C_{j0}\cos\frac{2\pi j}{P_1}(t-t_0) + S_{j0}\sin\frac{2\pi j}{P_1}(t-t_0)\right] + \sum_{k=1}^{m}\left[C_{0k}\cos\frac{2\pi k}{P_2}(t-t_0) + S_{0k}\sin\frac{2\pi k}{P_2}(t-t_0)\right]$$

- Components size ratio

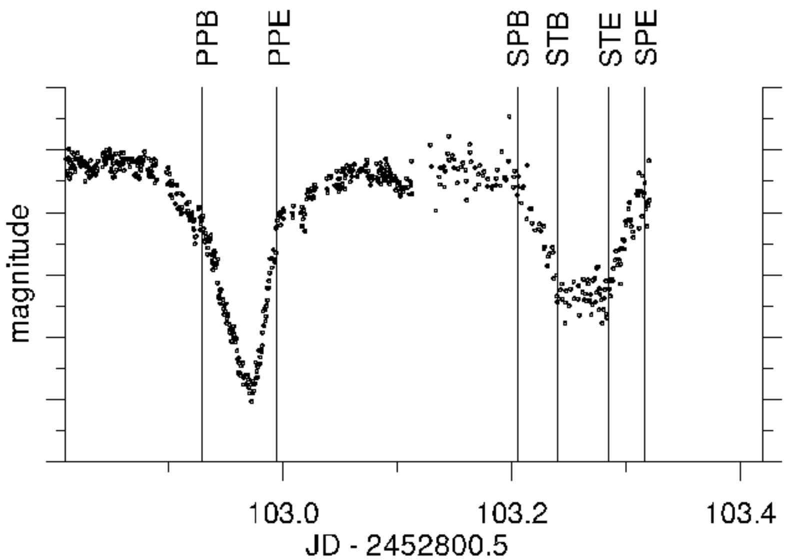
$$\Delta m = 2.5\log\left(\frac{C_0}{C_1}\right) = 2.5\log\left[1+\left(\frac{D_s}{D_p}\right)^2\right]$$

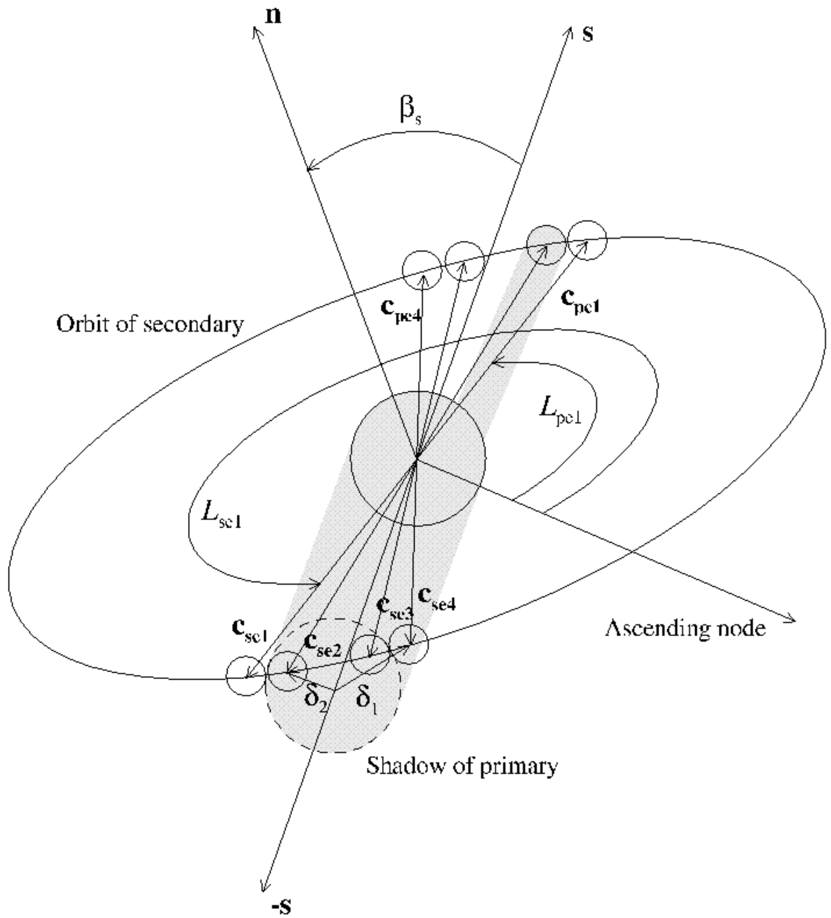


Pre-estimates of initial parameters

Sidereal orbital period and L_0 (argument of mean length of secondary for JD_0):

Visual identification of contacts:





Time-increasing L of contacts should lie on a straight line defined by

$$L' = nT + L_0$$

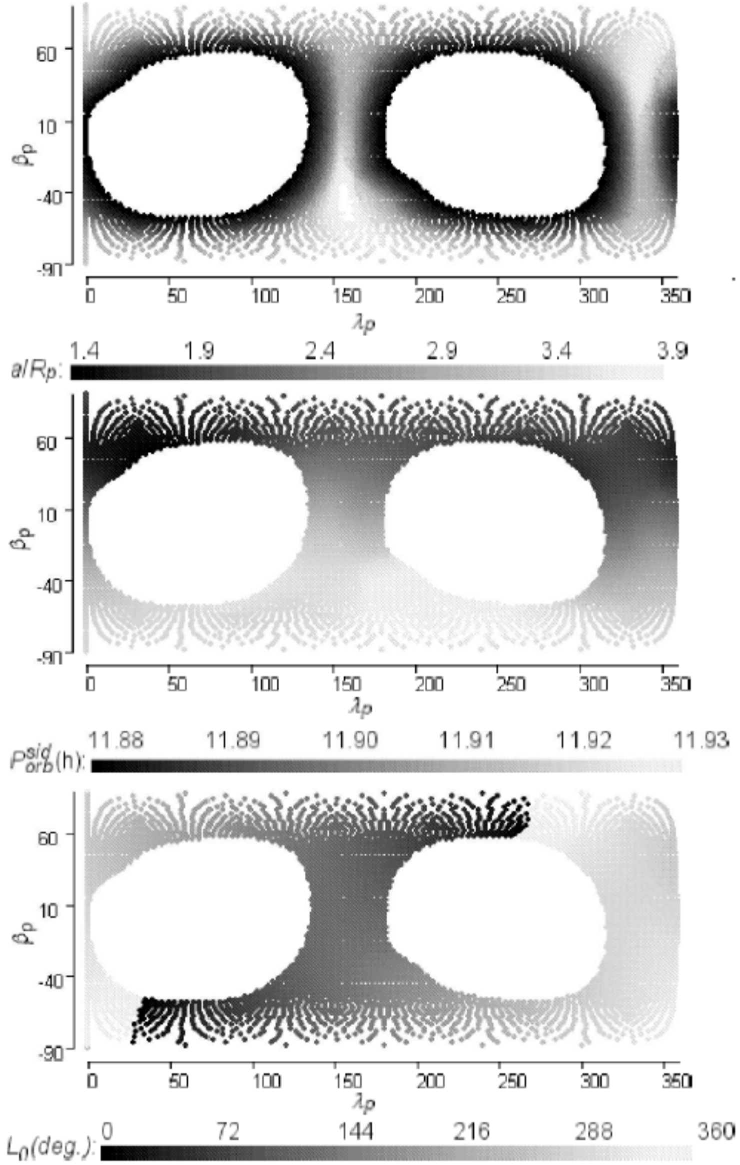
where $n = 2\pi/P_{sid}$.
This can be applied for fixed orbital pole only

Pre-estimates of initial parameters

Maps of parameters a/R_P, P_{orb} and L_0 precomputed from contacts identified in lightcurve for various directions of mutual orbit's normal (l_P,b_P).

From each starting point in the grid:

minimization using *Nelder and Mead simplex algorithm.*



Some results

Observational circumstances of modeled binary NEAs.

	Object	Apparition	Time span (d)	Geo. arc (°)	Hel. arc (°)	Phase angle (°)
(175706)	1996 FG_3	1998 Dec–99 Jan	36	30	27	14–32
(65803)	Didymos	2003 Nov–Dec	29	38	29	2–19
(66391)	1999 KW_4	2000 May–Jun[a]	35	90	17	62–76
		2001 May–Jun	18	99	9	33–66
(185851)	2000 DP_{107}	2000 Sep–Oct	8	19	7	30–38
(66063)	1998 RO_1	2002 Sep[a]	3	6	1	3–8
		2003 Sep	9	33	5	12–33
		2004 Sep	11	28	6	30–36

Estimated parameters of binary NEAs, with 3-σ errors.

Object (apparition)	Solution	RMS	D_2/D_1	a/A_1	λ_p (°)
(175706) 1996 FG_3 (1998)	I	0.018	$0.28^{+0.01}_{-0.02}$	$3.1^{+0.9}_{-0.5}$	242^{+96}_{-96}
(65803) Didymos (2003)	I	0.012	$0.22^{+0.01}_{-0.01}$	$2.8^{+0.2}_{-0.2}$	157^{+4}_{-7}
	II	0.012	$0.21^{+0.01}_{-0.01}$	$2.9^{+0.3}_{-0.2}$	329^{+11}_{-194}
(66391) 1999 KW_4 (2001)	I	0.036	$0.46^{+0.06}_{-0.06}$	$3.2^{+0.6}_{-0.5}$	341^{+9}_{-7}
(185851) 2000 DP_{107} (2000)	I	0.027	$0.43^{+0.3}_{-0.04}$	$5.0^{+2.0}_{-0.3}$	291^{+18}_{-26}
	II	0.026	$0.43^{+0.2}_{-0.05}$	$4.9^{+1.2}_{-0.2}$	31^{+23}_{-12}
(66063) 1998 RO_1 (2003)	I	0.027	$0.48^{+0.03}_{-0.03}$	$3.0^{+0.7}_{-0.4}$	277^{+180}_{-180}
(66063) 1998 RO_1 (2004)	I	0.025	$0.48^{+0.03}_{-0.03}$	$3.5^{+0.7}_{-0.6}$	274^{+17}_{-73}

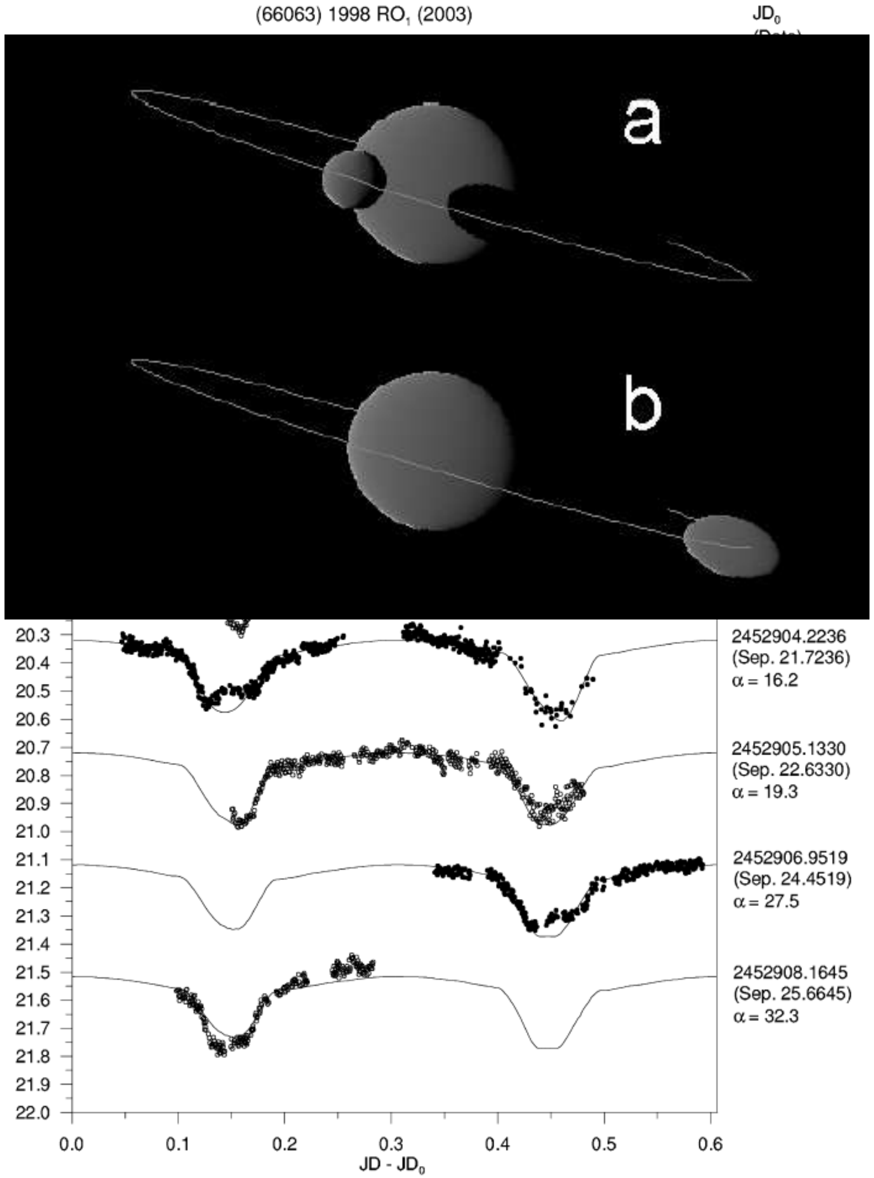
Object (apparition)	Solution	ω (°)	L_0 (°)	Epoch (MJD)	A_2/A_1
(175706) 1996 FG_3 (1998)	I	79^{+70}_{-93}	43^{+96}_{-96}	51150.6792	$0.33^{+0.07}_{-0.08}$
(65803) Didymos (2003)	I	349^{+13}_{-34}	120^{+3}_{-6}	52963.8922	$0.21^{+0.02}_{-0.02}$
	II	174^{+95}_{-25}	301^{+10}_{-191}	"	$0.20^{+0.02}_{-0.01}$
(66391) 1999 KW_4 (2001)	I	264^{+67}_{-64}	129^{+9}_{-8}	52054.0398	$0.51^{+0.08}_{-0.16}$
(185851) 2000 DP_{107} (2000)	I	328^{+16}_{-11}	270^{+20}_{-11}	51812.1522	$0.44^{+0.16}_{-0.09}$
	II	161^{+23}_{-19}	89^{+26}_{-18}	"	$0.37^{+0.20}_{-0.10}$
(66063) 1998 RO_1 (2003)	I	182^{+87}_{-176}	252^{+179}_{-180}	52898.8447	$0.56^{+0.09}_{-0.09}$
(66063) 1998 RO_1 (2004)	I	188^{+68}_{-15}	201^{+74}_{-12}	53258.1605	$0.45^{+0.25}_{-0.04}$

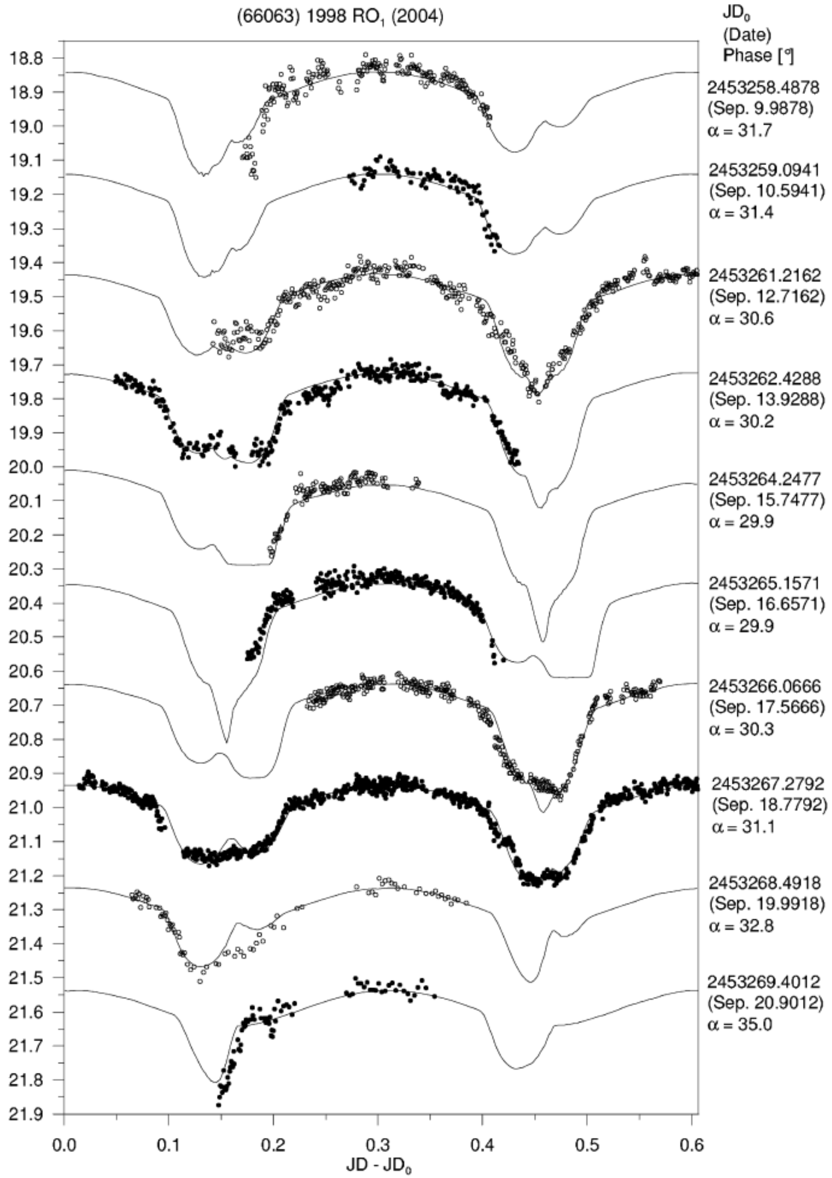
Estimated parameters of binary NEAs, with 3-σ errors.

Object (apparition)	Sol	λ_p (°)	β_p (°)	P_{orb}^{sid} (h)	e	
(175706) 1996 FG_3 (1998)	I	242^{+96}_{-96}	-84^{+14}_{-5}	$16.14^{+0.01}_{-0.01}$	$0.10^{+0.12}_{-0.10}$	$^{6}_{6}$
(65803) Didymos (2003)	I	157^{+4}_{-7}	$+19^{+45}_{-15}$	$11.906^{+0.004}_{-0.01}$	$0.09^{+0.07}_{-0.09}$	
	II	329^{+11}_{-194}	-70^{+25}_{-15}	$11.920^{+0.004}_{-0.006}$	$0.02^{+0.01}_{-0.02}$	$^{1}_{94}$
(66391) 1999 KW_4 (2001)	I	341^{+9}_{-7}	-56^{+20}_{-18}	$17.42^{+0.01}_{-0.03}$	$0.04^{+0.09}_{-0.04}$	
(185851) 2000 DP_{107} (2000)	I	291^{+18}_{-26}	$+80^{+7}_{-40}$	$42.09^{+0.13}_{-0.08}$	$0.05^{+0.19}_{-0.05}$	$^{3}_{6}$
	II	31^{+23}_{-12}	-61^{+18}_{-10}	$42.79^{+0.09}_{-0.11}$	$0.09^{+0.06}_{-0.06}$	
(66063) 1998 RO_1 (2003)	I	277^{+180}_{-180}	$+37^{+53}_{-2}$	$14.54^{+0.02}_{-0.01}$	$0.04^{+0.08}_{-0.04}$	$^{30}_{30}$
(66063) 1998 RO_1 (2004)	I	274^{+17}_{-73}	48^{+28}_{-6}	$14.54^{+0.03}_{-0.02}$	$0.06^{+0.04}_{-0.06}$	$^{7}_{3}$

Object (apparition)	Solu	A_2/A_1	A_1/C_1	A_2/C_2	ρ (g cm^{-3})	$_2/A_1$
(175706) 1996 FG_3 (1998)	I	$0.33^{+0.07}_{-0.08}$	$1.2^{+0.5}_{-0.2}$	$1.4^{+0.3}_{-0.2}$	$1.4^{+1.5}_{-0.6}$	$33^{+0.07}_{-0.08}$
(65803) Didymos (2003)	I	$0.21^{+0.02}_{-0.02}$	$1.0^{+0.3}_{-0.0}$	$1.0^{+0.1}_{-0.0}$	$1.7^{+0.6}_{-0.4}$	$21^{+0.02}_{-0.02}$
	II	$0.20^{+0.02}_{-0.01}$	$1.1^{+0.2}_{-0.1}$	$1.0^{+0.1}_{-0.0}$	$2.1^{+0.8}_{-0.5}$	$20^{+0.02}_{-0.01}$
(66391) 1999 KW_4 (2001)	I	$0.51^{+0.08}_{-0.16}$	$1.1^{+0.9}_{-0.1}$	$1.2^{+0.2}_{-0.2}$	$1.2^{+1.1}_{-0.5}$	$51^{+0.08}_{-0.16}$
(185851) 2000 DP_{107} (2000)	I	$0.44^{+0.16}_{-0.09}$	$1.2^{+1.1}_{-0.2}$	$1.2^{+0.1}_{-0.1}$	$0.8^{+1.1}_{-0.1}$	$44^{+0.16}_{-0.09}$
	II	$0.37^{+0.20}_{-0.10}$	$1.6^{+1.6}_{-0.6}$	$1.1^{+0.2}_{-0.1}$	$1.1^{+2.5}_{-0.6}$	$37^{+0.20}_{-0.10}$
(66063) 1998 RO_1 (2003)	I	$0.56^{+0.09}_{-0.09}$	$1.2^{+0.6}_{-0.2}$	$1.4^{+0.3}_{-0.1}$	$1.5^{+1.7}_{-0.6}$	$56^{+0.09}_{-0.09}$
(66063) 1998 RO_1 (2004)	I	$0.45^{+0.25}_{-0.04}$	$2.1^{+0.4}_{-1.1}$	$1.5^{+0.6}_{-0.1}$	$4.1^{+0.8}_{-2.8}$	$45^{+0.25}_{-0.04}$

Some results

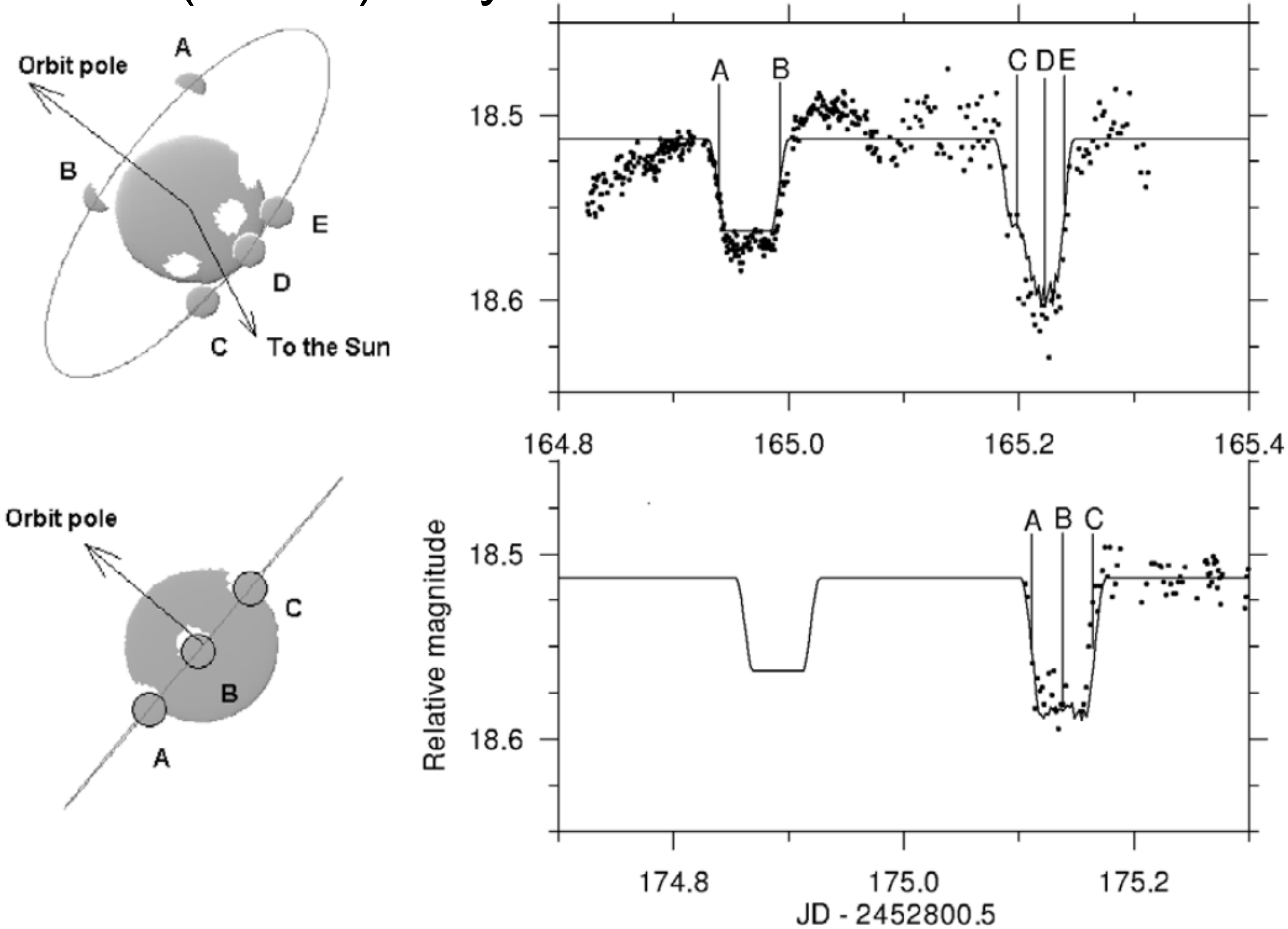




(Scheirich and Pravec, 2009)

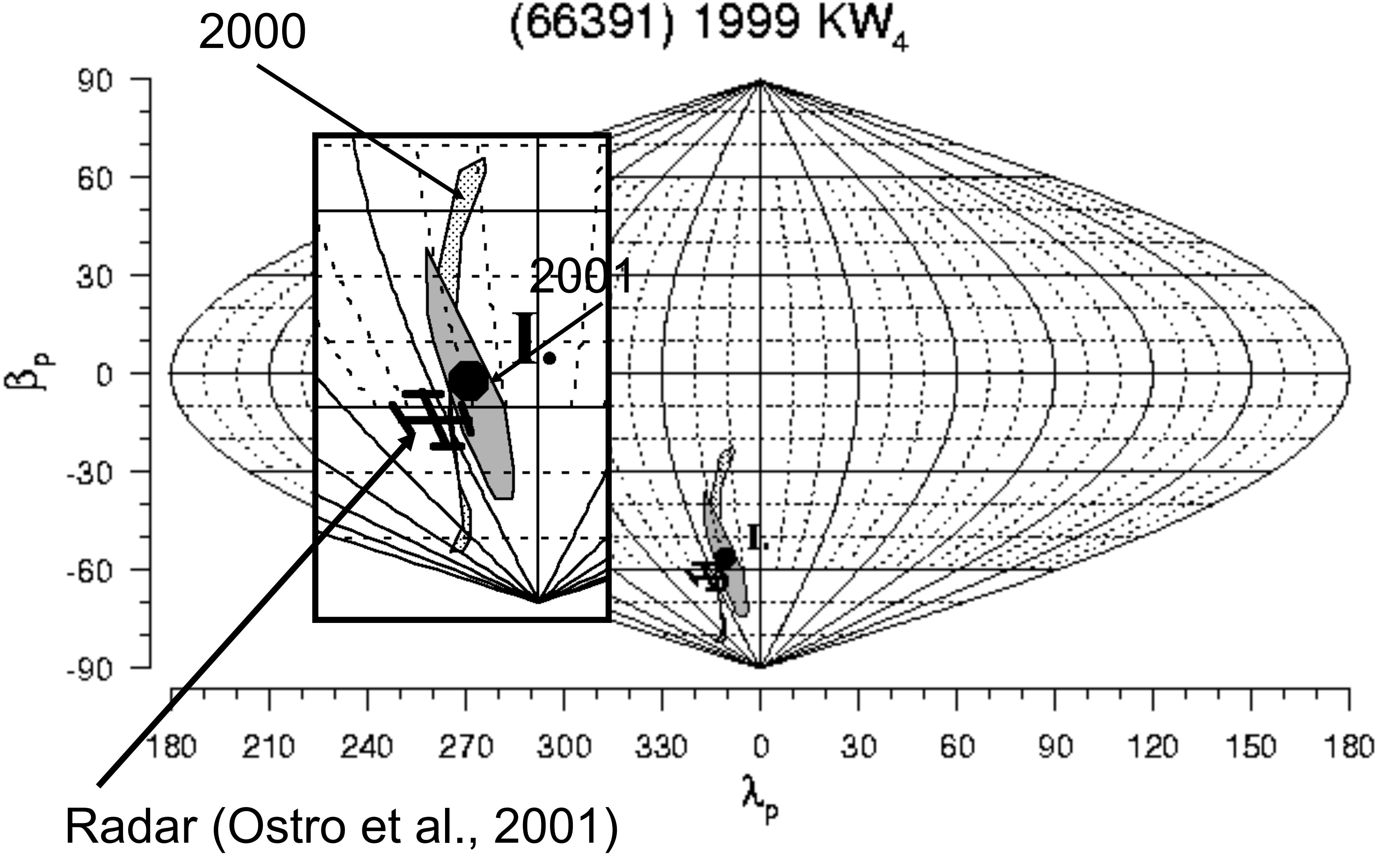
Some results

(65803) Didymos

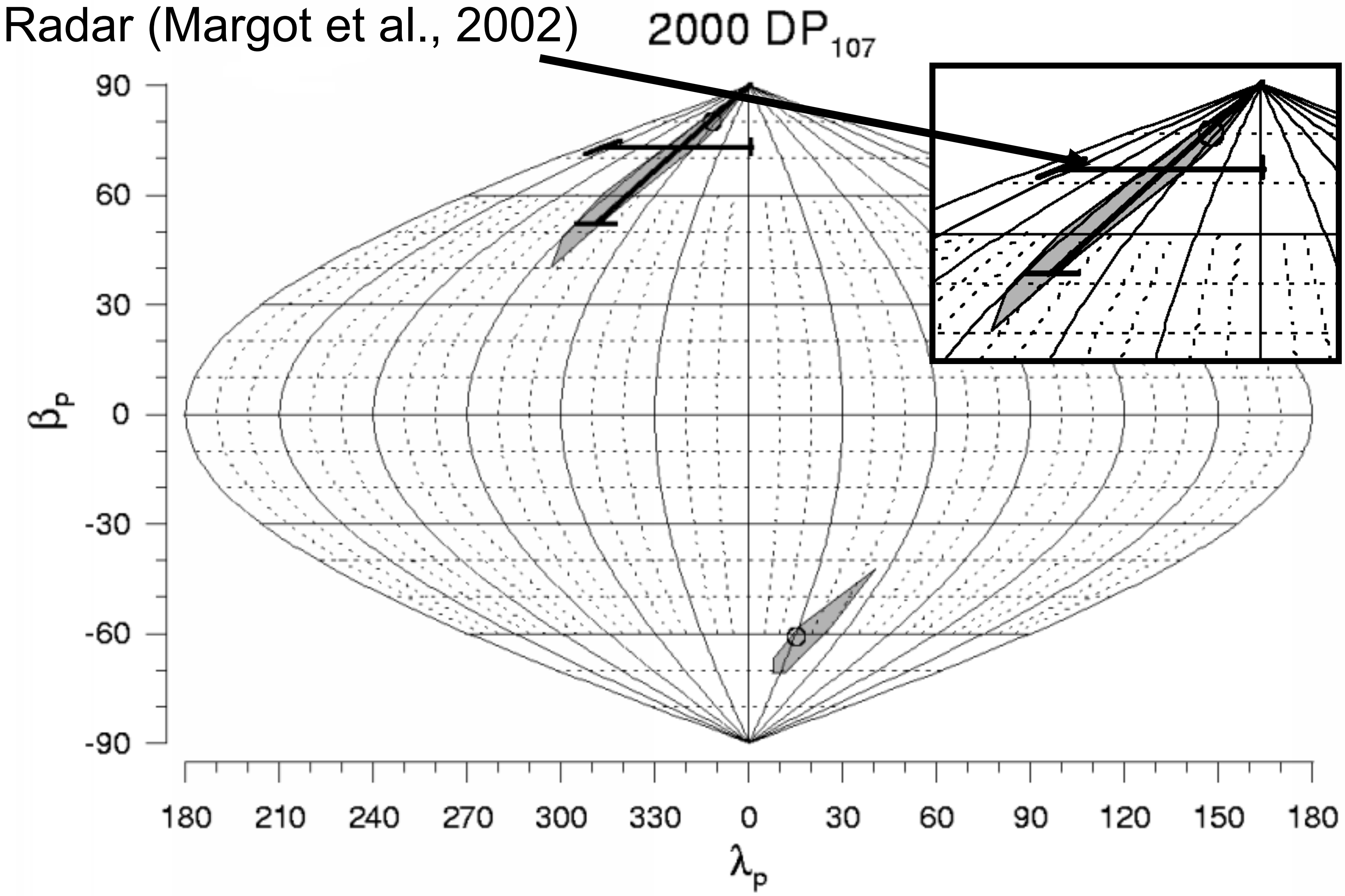


(Pravec et al. 2006)

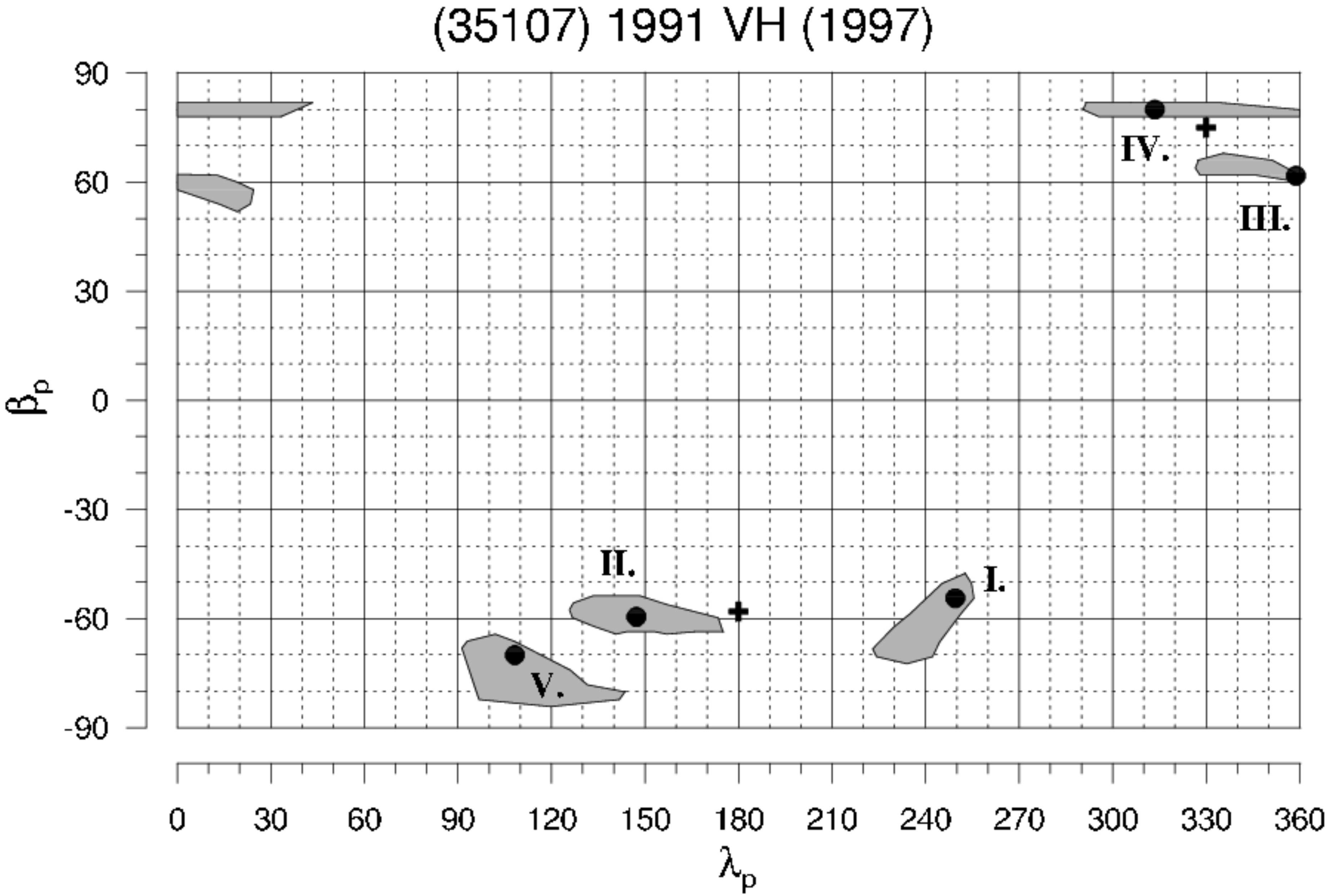
Matching with radar observations



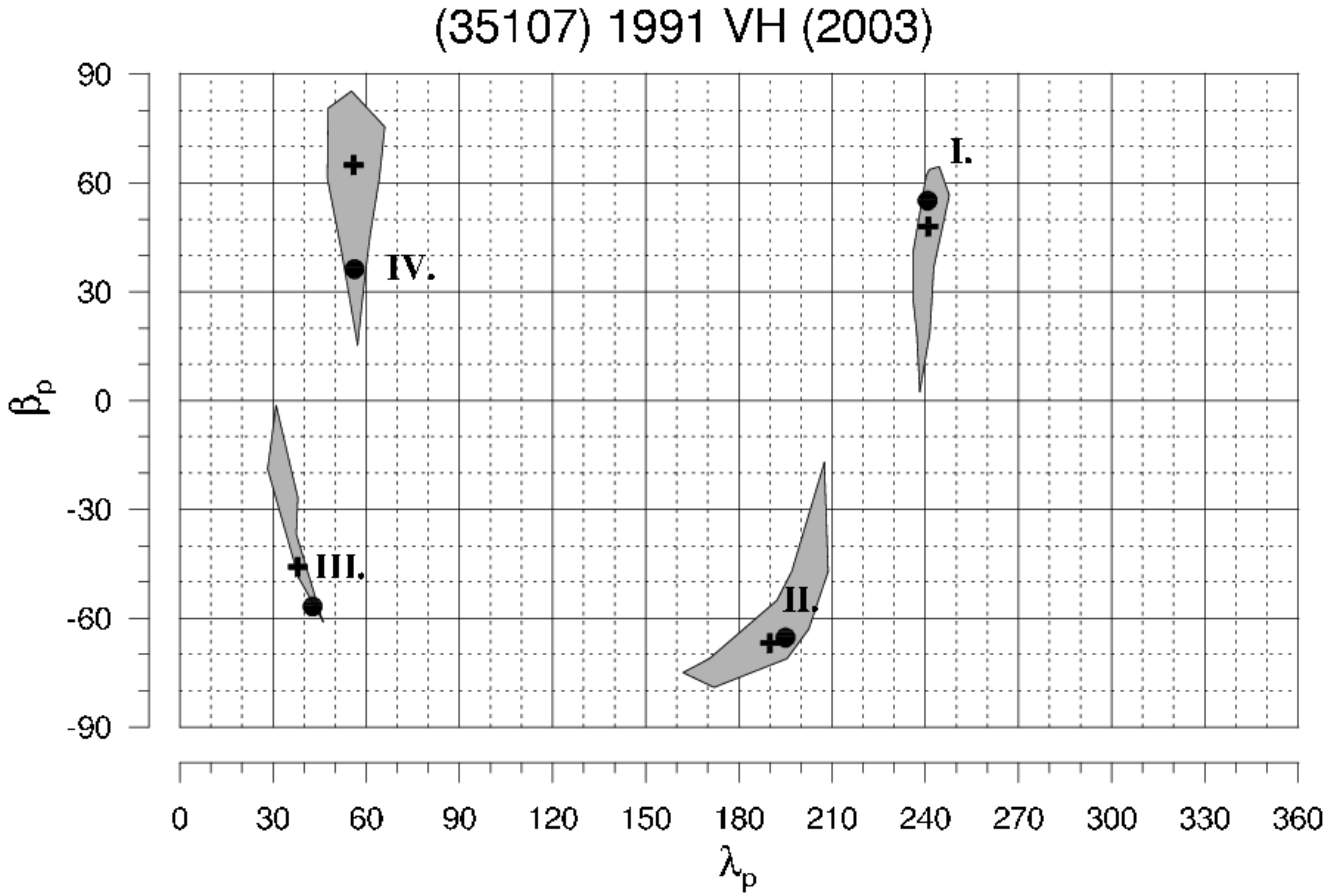
Matching with radar observations



Precession of mutual orbit?



Precession of mutual orbit?



Precession of mutual orbit?

(35107) 1991 VH – three periods in the lightcurve:

2.6236 h – (probably) primary's rotation

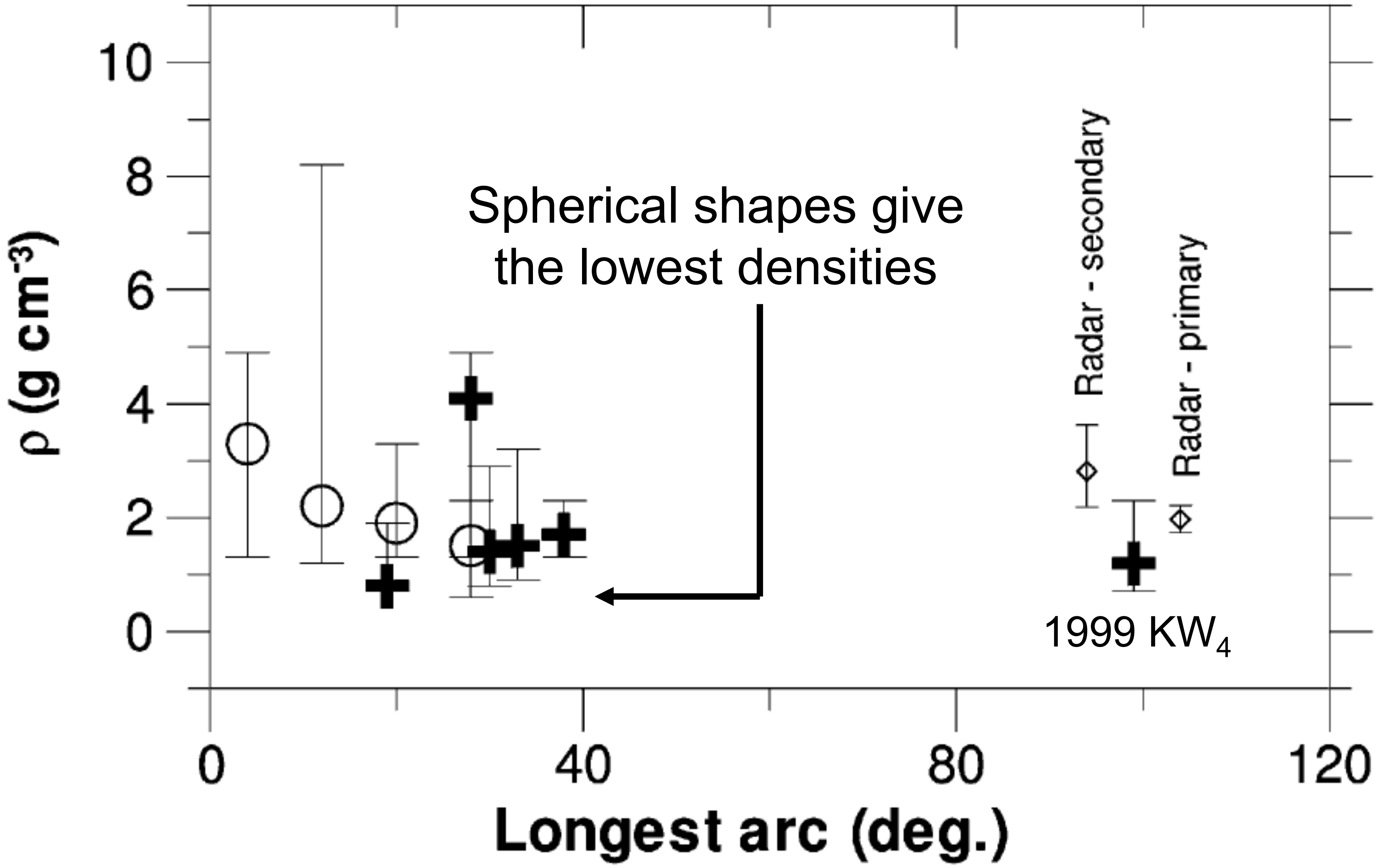
32.63 h – orbital period of secondary

12.836 h – ???

- rotation of secondary?
- precession of primary?

Uncertainty of bulk density

(Recycle the garbage with caution!)

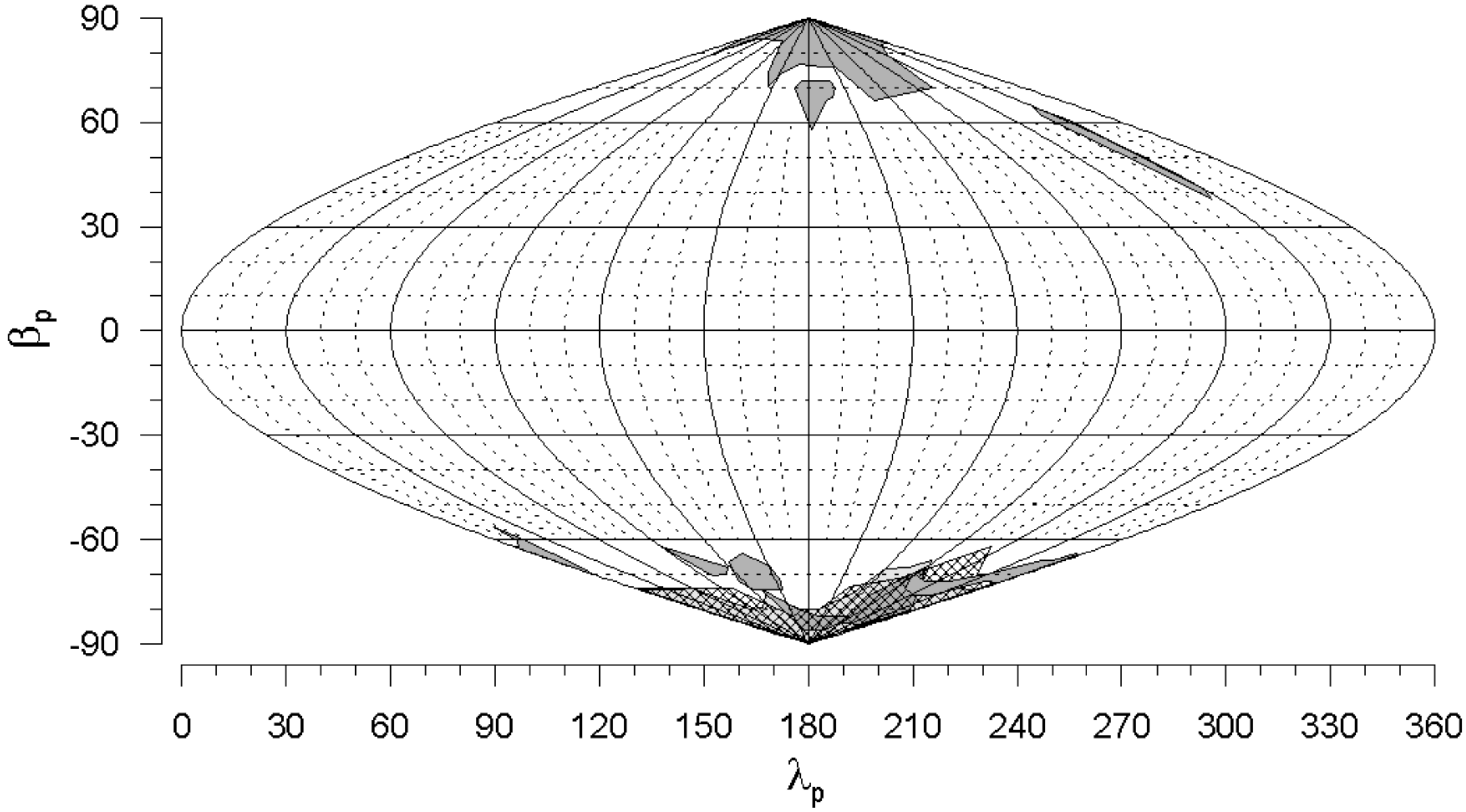


MBA multi-opposition data

Table 1: Parameters of 18 binary asteroids observed in more than one apparition

Binary system	Apparitions	D_1(km)	D_2/D_1	P_1(h)	P_{orb}(h)	P_2(h)	a_{orb}/D_1	L_{p} (°)	B_{p} (°)	ϵ (°)	$(a_1/c_1)_{\mathrm{max}}$	ϵ_{max}	a_{h}(AU)	i_{h}(°)
(1338) Duponta	07, 10	7.4	0.24 ±.02	3.85453 ±.00009	17.5680 ±.0001	(17.57) ±.01	2.0	0 - 360	+66 - +90	0 - 21	3.3[a]	0.14 (07)	2.264	4.82
(1453) Fennia	07, 09, 11	7.0	0.28 ±.02	4.4121 ±.0003	23.00351 ±.00005		2.6	89 - 118	−70 - −62	172 - 180	2.4[b]	0.03 (11)	1.897	23.68
(1830) Pogson	07, 08, 10	7.8	(0.30) ±.02	2.57003 ±.00006	24.24580 ±.00006		(2.5)	130 - 274	−86 - −74	162 - 180	3.4[c]	0.10 (08)	2.188	3.95
(2006) Polonskaya	05, 08, 10	5.5	(0.23) ±.03	3.1180 ±.0001	19.153[d]		(2.1)						2.325	4.92
(2044) Wirt[e]	05/06, 08, 10	5.6	0.25 ±.02	3.6897 ±.0003	18.976 ±.005	(18.97) ±.02	2.1	349 - 23	−72 - −52	120 - 143[f]	1.5	0.10 (05)	2.380	23.98
(2 pole solutions)					18.965 ±.006			168 - 203	+58 - +72	37 - 53				
(2577) Litva	09, 10	4.0	(0.34) ±.02	2.81292 ±.00009	35.8723 ±.0008		(3.2)	253 - 348	−84 - −68	158 - 178	2.3	0.08 (09)	1.904	22.91
(2754) Efimov	06, 08, 11	4.9	0.22 ±.02	2.44967 ±.00002	14.77578 ±.00008		1.8	0 - 360	−90 - −66	154 - 180	1.8[g]	0.08 (06)	2.228	5.71
(3309) Brorfelde	05, 09, 10	4.7	0.26 ±.02	2.5042 ±.0002	18.46444 ±.00003	18.45 ±.02	2.0	116 - 154	−74 - −64	168 - 180	2.1[h]	0.08 (10)	1.817	21.14
(3868) Mendoza	09, 10	8.3	0.17	2.77089 ±.02	12.1944 ±.00005	±.00008	1.5						2.333	8.10
(4029) Bridges	06, 07, 10	7.7	0.27 ±.03	3.5750 ±.0004	16.31701 ±.00004		1.9	0 - 360	−90 - −62	157 - 180	3.5	0.17 (06)	2.525	5.44
(5477) Holmes	05, 07	2.9	0.39 ±.02	2.9940 ±.0002	24.4036 ±.0002	(24.41) ±.01	2.5	320 - 332	+38 - +64[i]	5 - 30[i]	2.0[j]	0.05 (05)	1.917	22.55
(5905) Johnson	05, 08	3.6	0.38 ±.02	3.7823 ±.0002	21.75639 ±.00006		2.3	30 - 58	+60 - +76	0 - 14			1.910	27.52
(2 pole solutions)					21.79699 ±.00009			210 - 254	−56 - −76	167 - 180				
(6084) Bascom[k]	05/06, 08	5.8	0.37 ±.02	2.7453 ±.0002	43.51 ±.02	(43.5) ±.1	3.7	267 - 378	−76 - −56	127 - 169	2.9	0.15 (06)	2.313	23.01
(6244) Okamoto	06, 09	4.4	0.25 ±.02	2.8957 ±.0003	20.3105 ±.0002		2.2	0 - 360	+54 - +90[l]	0 - 33[l]			2.160	5.40
(2 pole solutions)					20.3232 ±.0002			0 - 360	−90 - −58[m]	151 - 180[m]				
(6265) 1985 TW3	07, 10	5.2	(0.32) ±.02	2.7092 ±.0001	15.86[n]		1.9						2.166	4.11
(9617) Grahamchapman	06, 08	2.8	(0.27) ±.03	2.28561 ±.00006	19.3817 ±.0004		2.1	0 - 360	+48 - +90[p]	0 - 38[p]			2.224	6.14
(2 pole solutions)					19.3915 ±.0004			0 - 360	−90 - −50[q]	141 - 180[q]				

MBA multi-opposition data



MBA multi-opposition data

	Oppositions	P_{orb} (hours)	3[illegible] (s)	M after 5 years (degrees)
(1453) Fennia	07,09,11	23.00351	± 0.2	± 2
(1830) Pogson	07,08,10	24.24580	± 0.2	± 1
(2754) Efimov	06,08,11	14.77578	± 0.3	± 6
(3309) Brorfelde	05,09,10	18.46444	± 0.1	± 1
(4029) Bridges	06,07,10	16.31701	± 0.1	± 2

Three-period systems among MBA

- (1830) Pogson: 2.57 h; 3.26 h; 24.26 h (orb.)
- (2006) Polonskaya: 3.12 h; 6.66 h; 19.15 h (orb.)
- (2577) Litva: 2.81 h; 5.68 h; 35.87 h (orb.)

The second rotational component does not disappear during the secondary event → it's not the rotation of the secondary → indication of the third object in the system.

(Pravec et al., submited to Icarus)

Conclusions

Photometry of NEA and small MBA binaries

- requires:
  - distribution of observers among the world
  - sub-meter to meter-class telescopes
- gives:
  - unique (in many cases) orbital poles, periods, and other parameters
  - constraints on theories of binaries' origin and evolution
- does not give:
  - (accurate) densities!