Binární, párové a vícenásobné asteroidy
(Asteroid spin-up fission systems)

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PROGRAM CEZHRANIČNEJ SPOLUPRÁCE
2007 2013
SLOVENSKÁ REPUBLIKA
ČESKÁ REPUBLIKA
EURÓPSKA ÚNIA
EURÓPSKY FOND REGIONÁLNEHO ROZVOJA
SPOLOČNE BEZ HRANÍC
euroregion BÍLÉ - BIELE KARPATY
FOND MIKROPROJEKTŮ

NEOSource project
1.54-m Danish telescope, La Silla

Study of non-gravitational asteroid evolution processes via photometric observations
PI Petr Pravec, Astronomical Institute AS CR Ondřejov
Co-PI David Vokrouhlický, Astronomical Institute MFF UK, Prague

2012-2016, remote observations on 90 nights/year with the 1.54-m telescope at La Silla

The observations will start in October 2012. Allsky camera

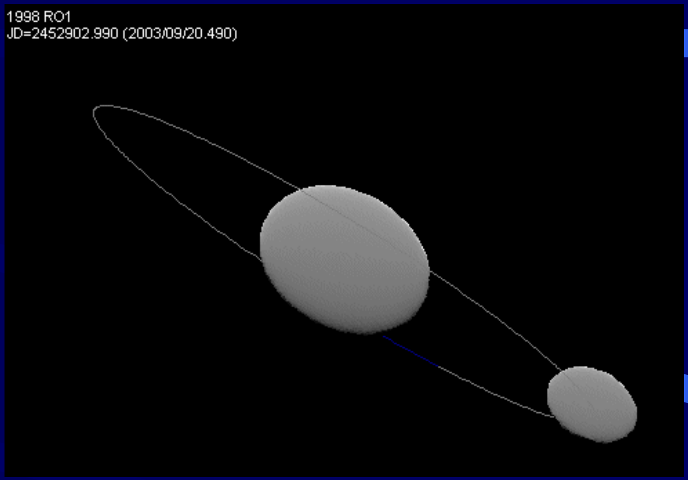
Binary planet

Binary asteroids (bound and unbound)

Systems of 2 or more components, bound or unbound, among small asteroids.

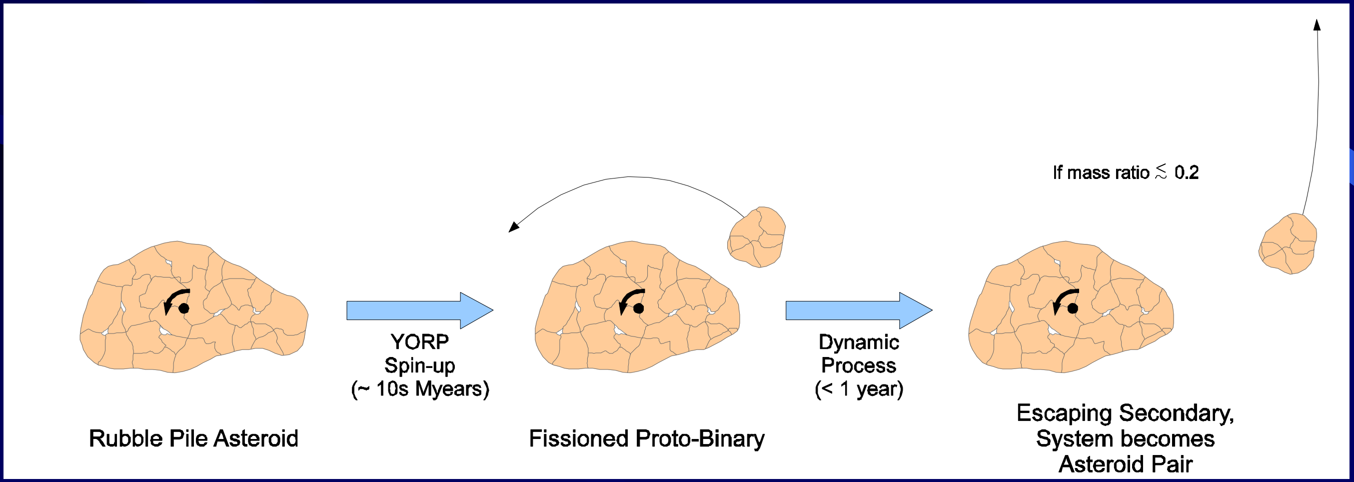
Bound asteroids – Binary/ternary systems:

(Ostro et al. 2006)



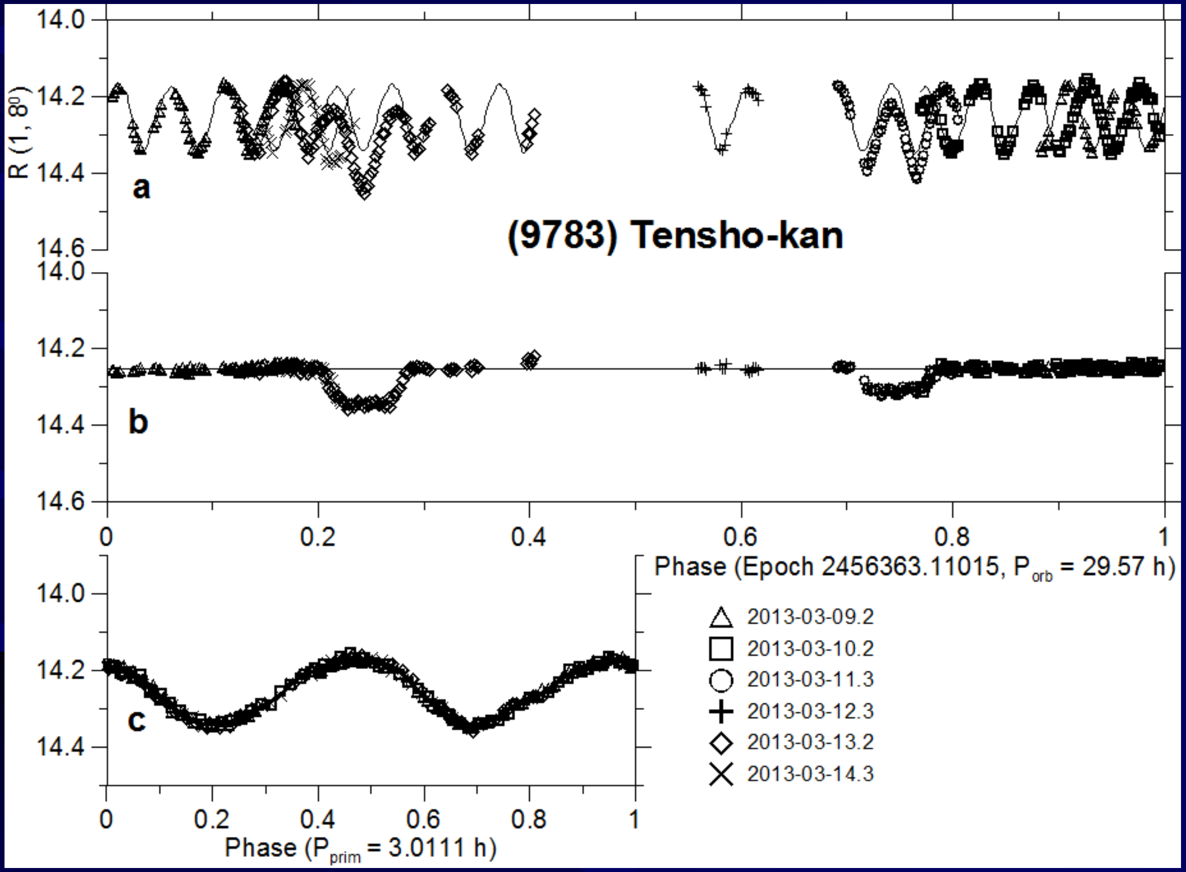
(Scheirich and Pravec 2009)

Unbound asteroids – Asteroid pairs:



(Pravec et al. 2010)

Photometric observations of a binary asteroid



Binary formation theories

<u>Ejecta from large asteroidal impacts</u> *(e.g., Durda et al. 2004)* – does not predict the observed critical spin.

<u>Tidal disruptions during close encounters with terrestrial planets</u> *(Bottke et al. 1996; Richardson and Walsh)* – does not work in the main belt, so, it cannot be a formation mechanism for MB binaries. It may contribute to and shape the population of NEA binaries.

Fig. 4. Snapshots of a tidal disruption simulation that led to the formation of a binary asteroid. The frames span about 72 h.

(Walsh and Richardson 2006)

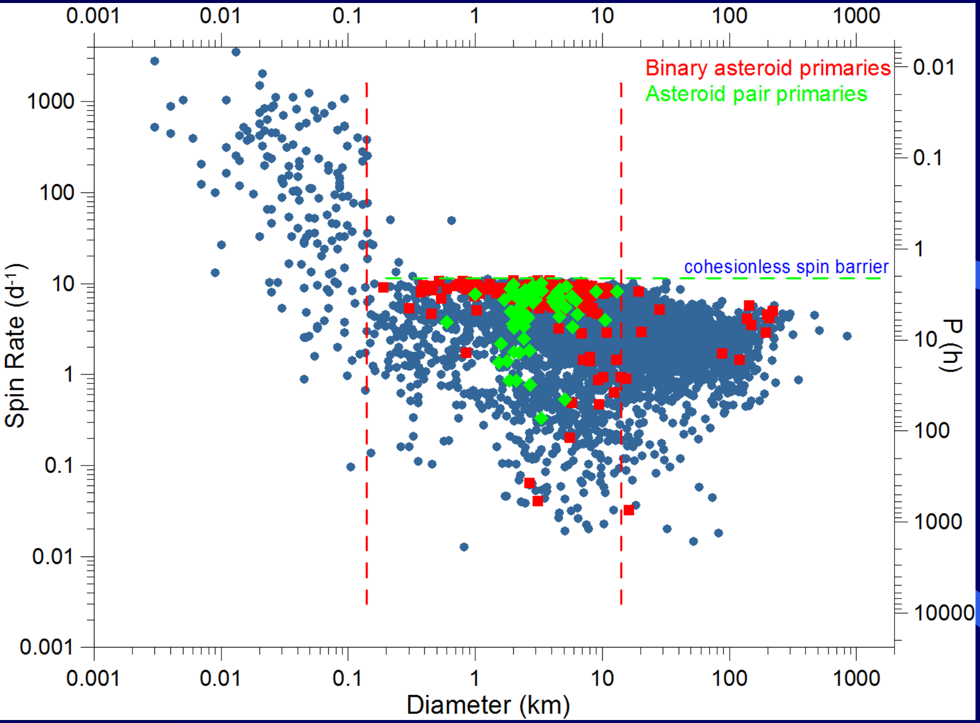
<u>Fission of critically spinning parent bodies spun up by YORP</u> *(e.g., Walsh et al. 2008)* – appears to be a primary formation mechanism for small close binaries.

Small asteroids as cohesionless structures

Small asteroids –
cohesionless bodies, easily breakable

Asteroids with sizes within about a factor of 10 around a diameter of 1 km show a number of characteristics indicating they are predominantly cohesionless structures.

Zero or negligible tensile strength indicated by the existence of a 'barrier' against spins faster than *P* = 2.2 h:

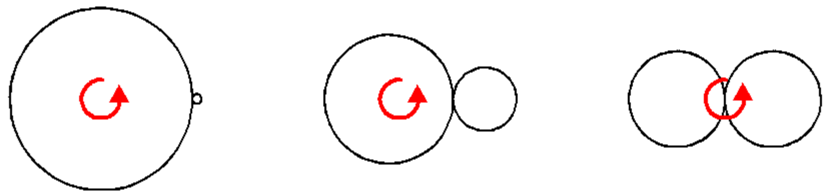


At the spin barrier – balance between the gravity and centrifugal acceleration at the equator of a sphere with ρ ~ 3 g/cm^3, taking into account also the angle of friction (30-40°).

where ω_{csph} is the critical spin rate for the sphere

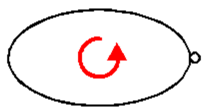
$$\omega_{csph} = \sqrt{\frac{4}{3}\pi\rho G},$$

Small asteroids –
cohesionless bodies, easily breakable



$R_2 \ll R_1$ $\quad X \equiv \frac{R_2}{R_1}$ $\quad R_2 = R_1$

$$\omega_c = \sqrt{\frac{4\pi\rho G}{3}} \qquad \omega_c = \sqrt{\frac{4\pi\rho G}{3}}\sqrt{\frac{1}{(1+X)^3(1-\frac{1}{1+X^{-3}})}} \qquad \omega_c = \sqrt{\frac{\pi\rho G}{3}}$$



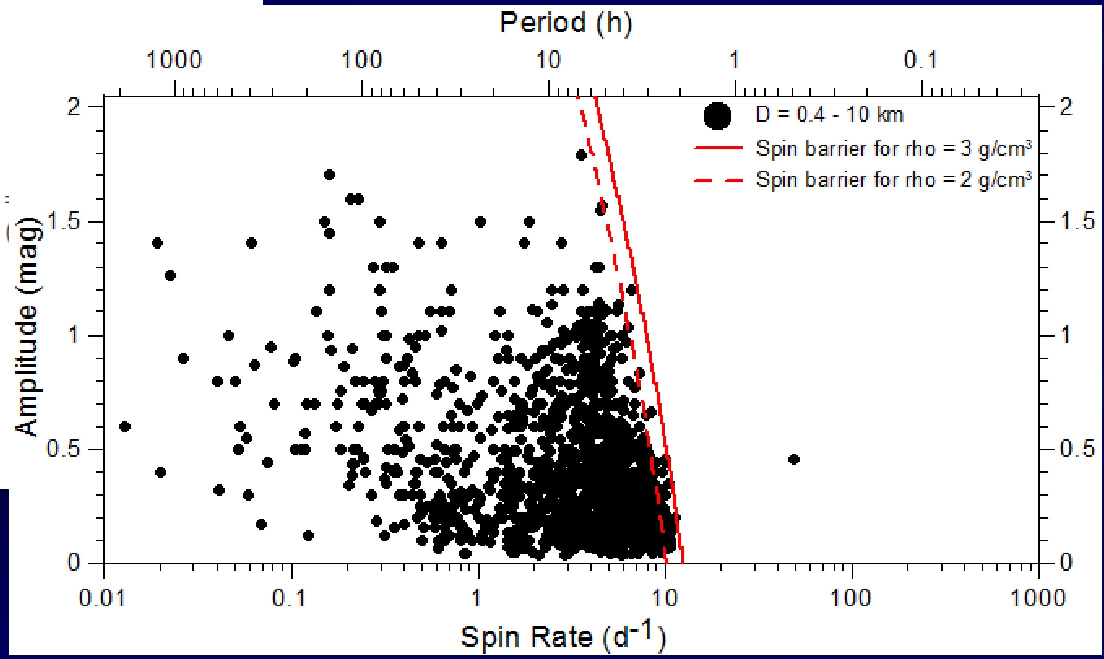
The critical spin rate $\omega_c(90°)$ for a prolate spheroid ($a \geq b$ … of friction $\phi = 90°$ has been derived by Richardson et al. (… formula

$$\omega_c(90°) = \frac{\sqrt{2\pi\rho G}}{w^{3/2}}\sqrt{(w^2-1)\left[2w + ln\left(\frac{1-w}{1+w}\right)\right]},$$

where $w \equiv \sqrt{1-(b/a)^2}$.

The spin barrier in the 2nd dimension (asteroid elongation).

Vast majority of asteroids larger than ~0.2 km rotate slower than the critical rate for bulk density 3 g/cm^3.



Accounting for angles of friction < 90° with theory of cohesionless elastic-plastic solid bodies (Holsapple 2001, 2004).

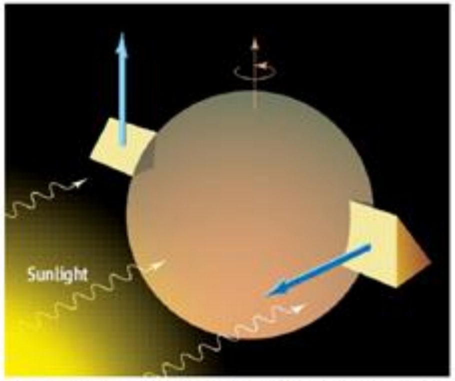
YORP – a spin-up mechanism

Spin-up fission of asteroids

A mechanism to spin up an asteroid to the critical spin (disruption) frequency is provided by the Yarkovsky-O'Keefe-Radzievskii-Paddack (YORP) effect.

After fission, a process of exchange of the angular momentum and energy between the components leads to a few possible outcomes :

- Long-term stable or slowly evolving bound asteroids (binary/ternary systems)
- Unbound asteroids (asteroid pairs)
- Contact binary/re-shaped asteroid



Spinning in the Sun. Sunlight speeds up rotation due to reflection off the vertical and slated faces of the wedges (blue arrows). Infrared radiation emitted by the faces also causes speed-up. If the body spins in the opposite sense, then YORP will slow it down.

(Rubincam and Paddack 2007)

162 S.A. Jacobson, D.J. Scheeres / Icarus 214 (2011) 161–178

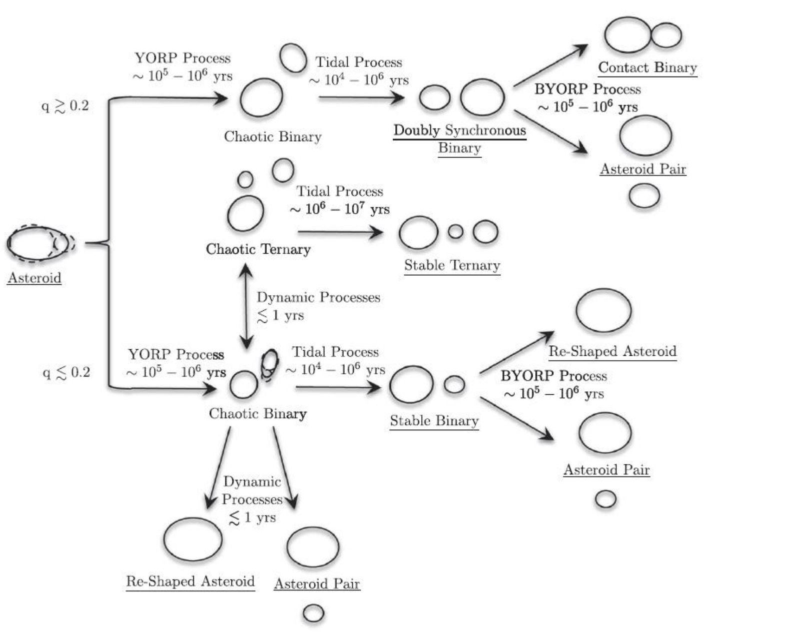
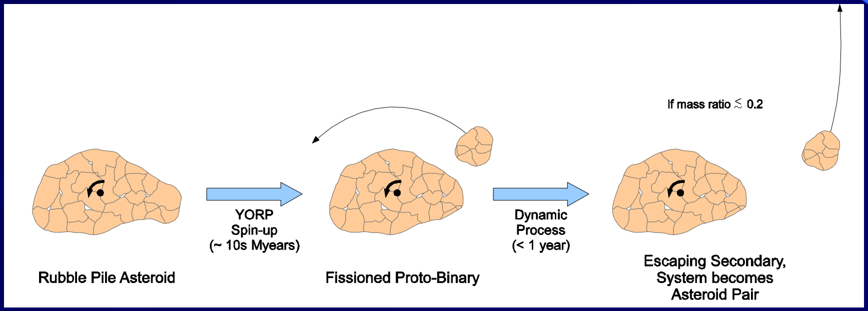


Fig. 1. Evolutionary tracks for an NEA. q is the rotational fission component mass ratio. Arrows indicate the direction of evolution along with the process propelling the evolution and a typical timescale. Simple schematics show evolutionary states, an underline indicates an observed asteroid class. Stable ternaries are rare, and so their continued evolution is not described here, although it should be noted that ternaries may be formed via multiple primary fission events. It is important to note that the eventual outcomes are single asteroids (re-shaped asteroids, contact binaries, each member of asteroid pairs), so this evolutionary process represents a binary cycle.

(Jacobson and Scheeres 2011)



(Pravec et al. 2010)

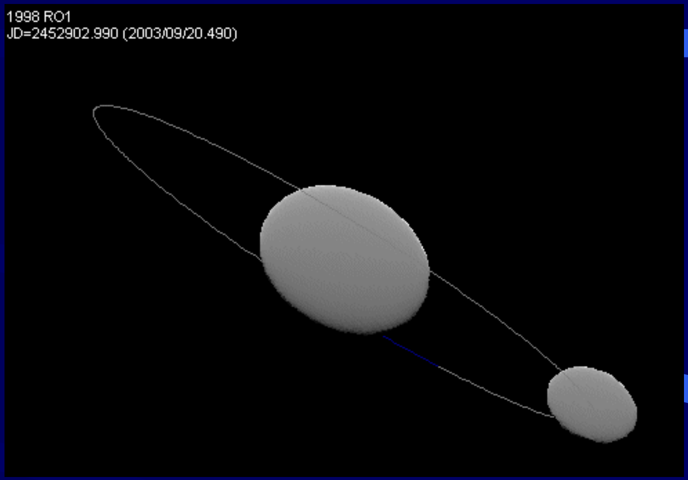
Asteroid spin-up fission systems

Observed systems:

Bound asteroids – Binary/ternary systems:

- Studied with radar (among NEAs) and photometry (among NEAs and MBAs)

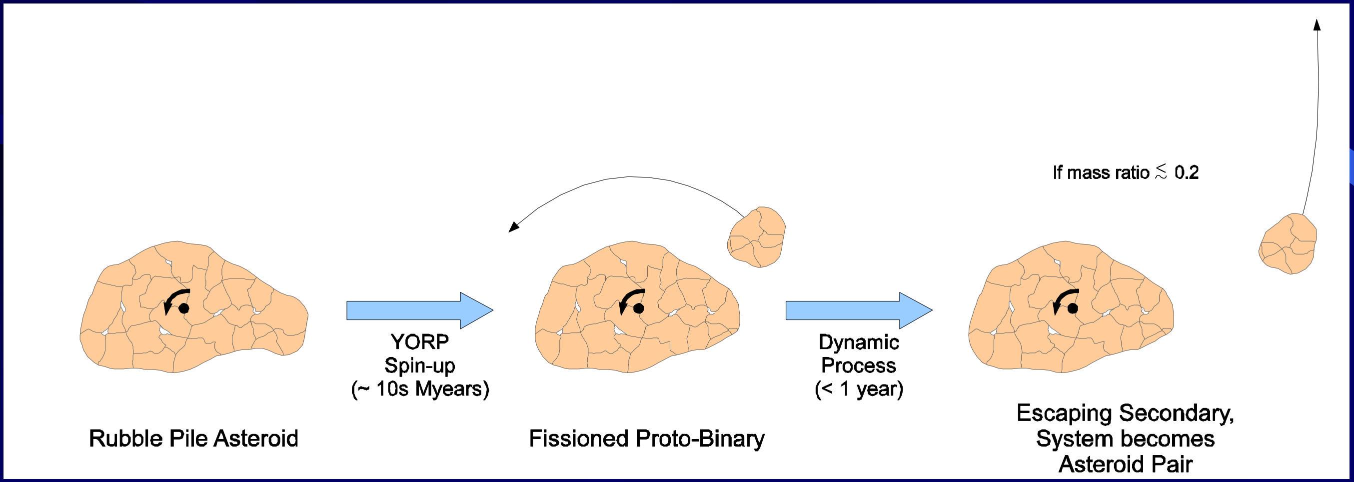
(Ostro et al. 2006)



(Scheirich and Pravec 2009)

Unbound asteroids – Asteroid pairs:

- Recognizable among MBAs
- Age <~ 2 Myr



(Pravec et al. 2010)

These two groups are not mutually exclusive; there exist paired binaries/ternaries: (3749) Balam, (8306) Shoko

Spin-up fission asteroid systems

Current sample:

<u>Binary/ternary systems</u> (bound asteroids):

144 systems with D_1 < 15 km. Of them

- 48 are NEAs
- 96 are MBAs/MCs.

(Pravec and Harris 2007, update June 2014):

<u>Asteroid pairs</u> (unbound asteroids):

179 pairs identified (all MBAs).

- Most of them confirmed with backward orbital integrations showing convergence.
- Some of them have got also spectral observations *(Polishook et al. 2014; Wolters et al. 2014, and other works)* showing largely similar spectra.

A contamination of the sample by coincidental pairs is small.

(Vokrouhlický and Nesvorný 2008, Pravec and Vokrouhlický 2009, Pravec et al. 2010, plus others in prep.)

Sizes: D_1 = ~0.15 to ~13 km

<u>Primary sizes:</u>

<u>Largest</u> D_1 ~ 13 km

(1741) Giclas: 13.1 km

(939) Isberga: 10.6 km

(both Masiero et al. 2012, unc. ~10%)

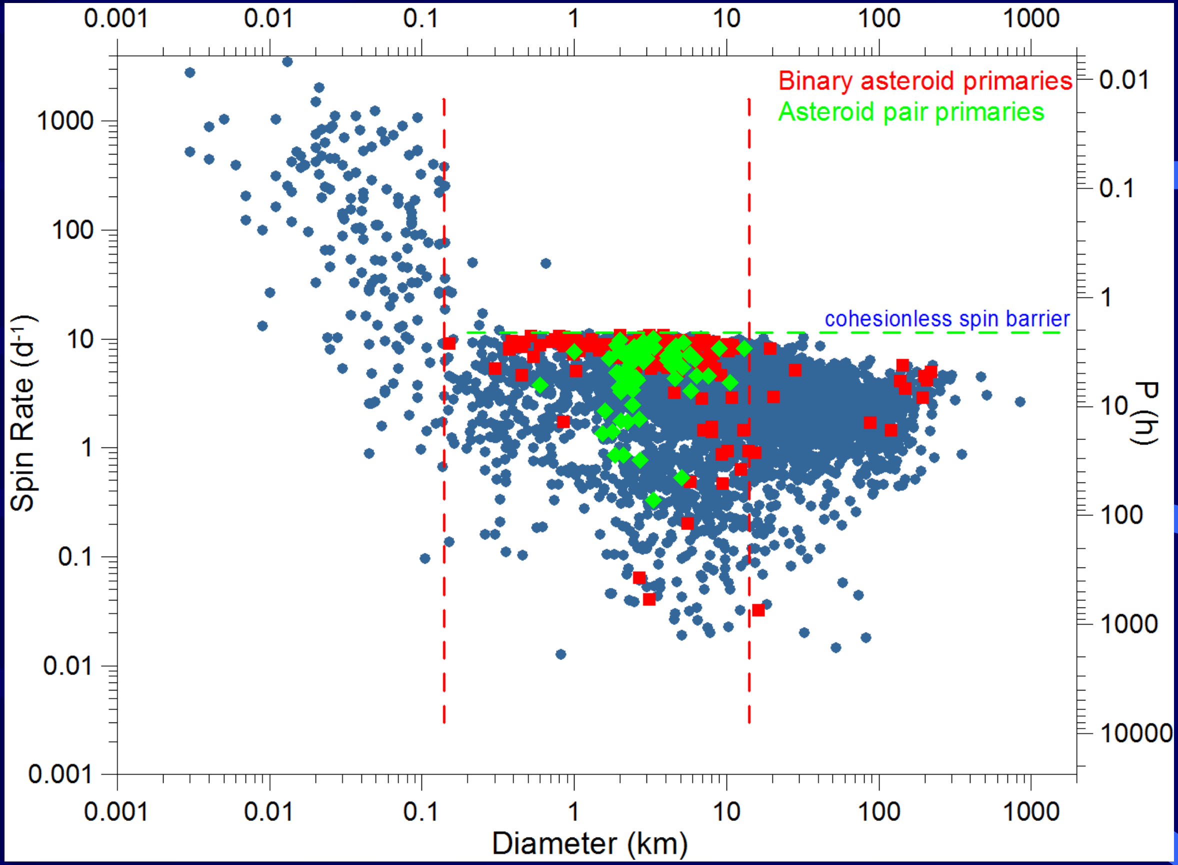
<u>Smallest</u> D_1 ~ 0.15 km

2004 FG11: 0.15 ± 0.03 km

(Taylor et al. 2012)

2003 SS84: 0.12 km

(Nolan et al. 2003, no unc. given)



This size range coincides with where we observe the spin barrier – gravity dominated regime, cohesionless, 'rubble-pile' asteroid structure implied.

At the spin barrier – balance between the gravity and centrifugal acceleration at the equator of a sphere with ρ *~ 3 g/cm³, taking into account also the angle of friction (30-40°).*

where ω_{csph} is the critical spin rate for the sphere

$$\omega_{csph} = \sqrt{\frac{4}{3}\pi \rho G},$$

Evidence for formation by rotational fission

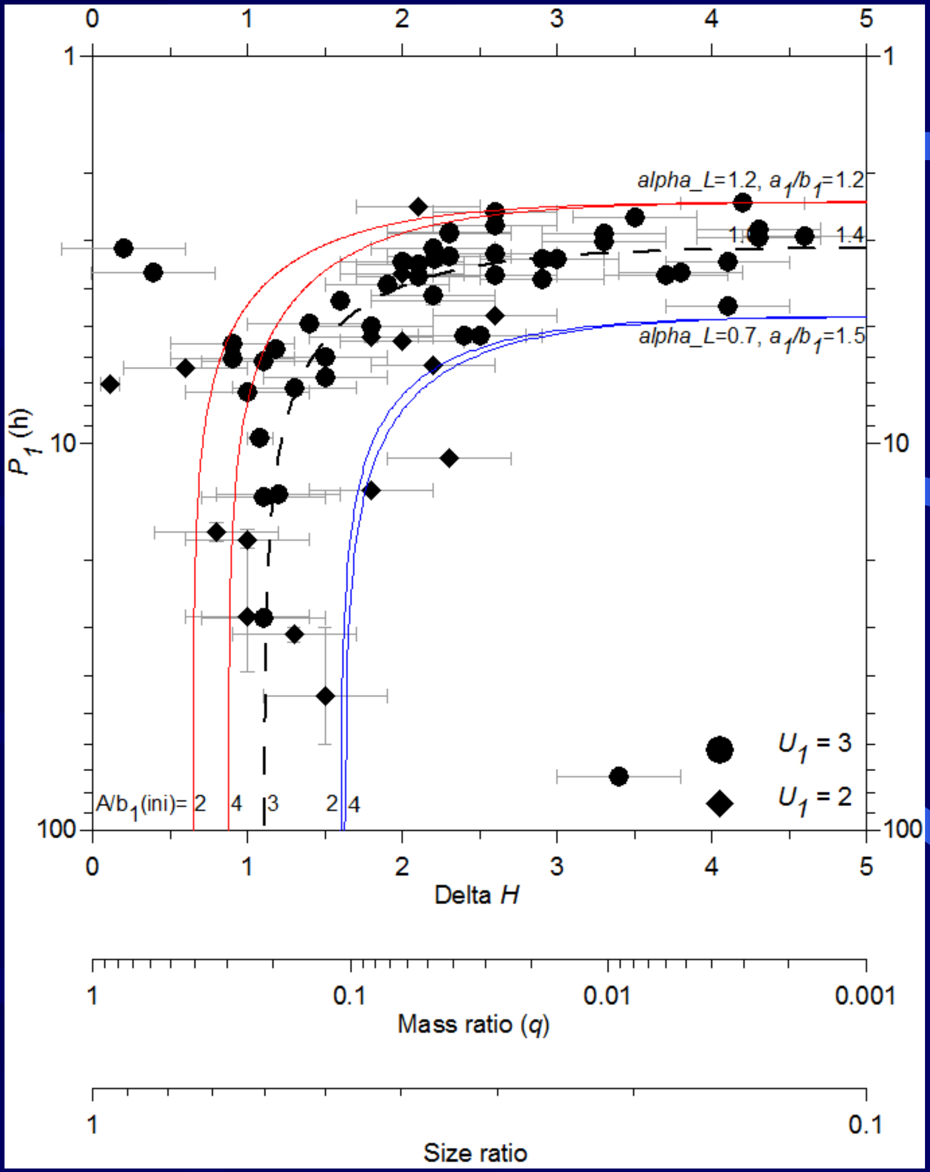
Asteroid pairs - correlation between P_1 and q

The observed correlation is an evidence for formation of asteroid pairs by rotational fission.
(Scheeres 2007, Pravec et al. 2010)

P_1 measured for 64 asteroid pair primaries.

The correlation between P_1 and q holds for 60:

- Low-mass ratio pairs *(q <~0.05):* Primary rotations not substantially slowed down in the separation process, P_1 = 2.4 to 5 h.
- Medium-mass ratio pairs (q = 0.05 to ~0.2): Primaries slowed down as a substantial amount of angular momentum taken away by the escaped secondary.
- High-mass ratio pairs (q > 0.2): Three observed cases require an additional supply of angular momentum.



Total angular momentum of binaries

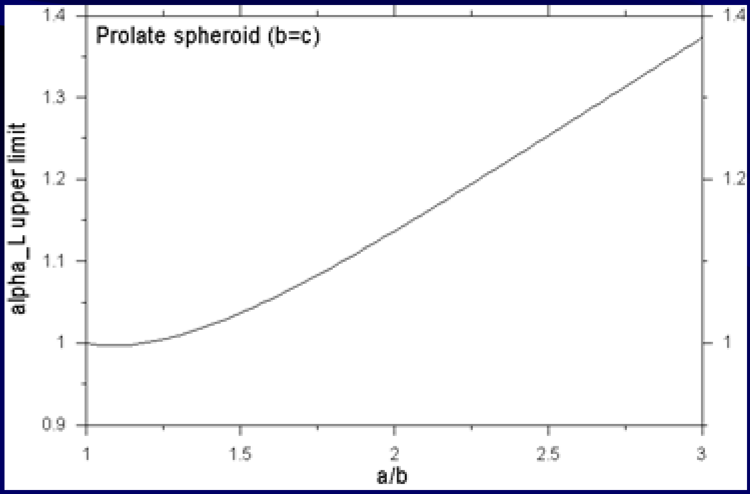
Small binaries have the total angular momentum close to critical, as expected for systems originating from critically spinning rubble piles. *(Pravec and Harris 2007, updated)*

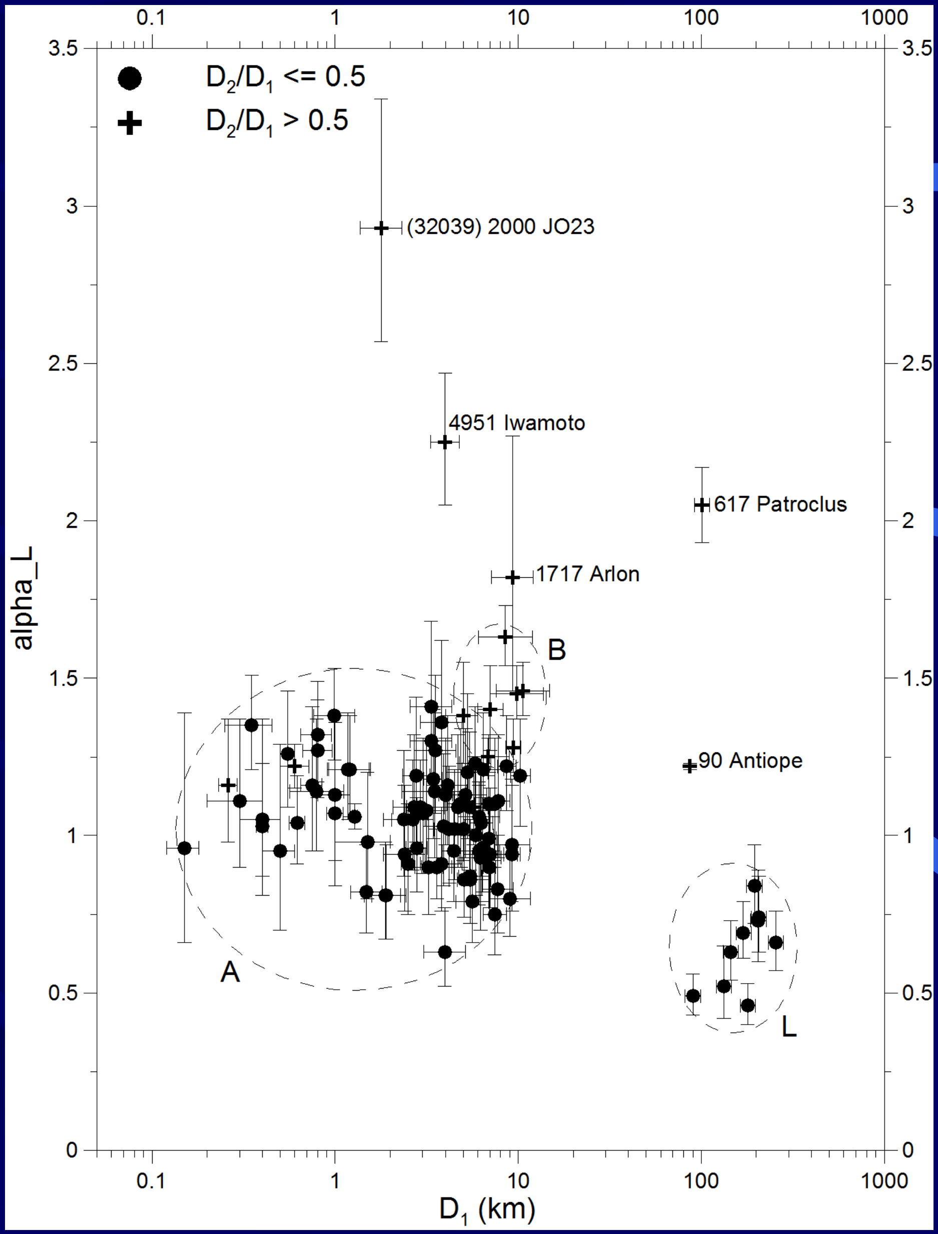
The ratio α_L is then expressed as

$$\alpha_L \equiv \frac{L_1 + L_2 + L_{orb}}{L_{eqsph}} =$$

$$= \frac{\left[1 + \left(\frac{a_1}{b_1}\right)^2\right]\omega_1 + q\left(\frac{b_2}{b_1}\right)^2\left[1 + \left(\frac{a_2}{b_2}\right)^2\right]\omega_2}{2(1+q)^{5/3}\left(\nu\frac{a_1}{b_1}\frac{c_1}{b_1}\right)^{2/3}\omega_{csph}} +$$

$$+ \frac{5}{2}\frac{q}{(1+q)^2}\left(\frac{\omega_{csph}}{n}\right)^{\frac{1}{3}}(1-e^2)^{1/2},$$

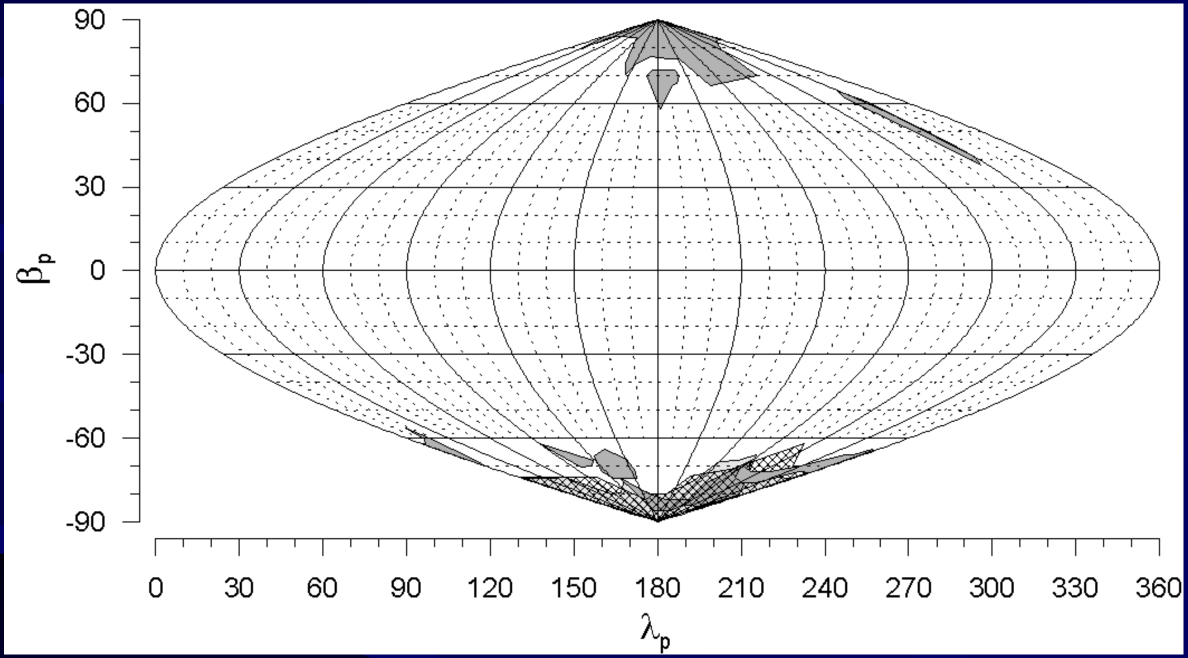




Evidence for spin up by YORP

Anisotropic orbit pole distribution

Orbital poles of 18 small binary MBAs (D_1 = 3 to 8 km) show highly anisotropic distribution: they are oriented preferentially <u>up/down-right</u> *(Pravec et al. 2012)*

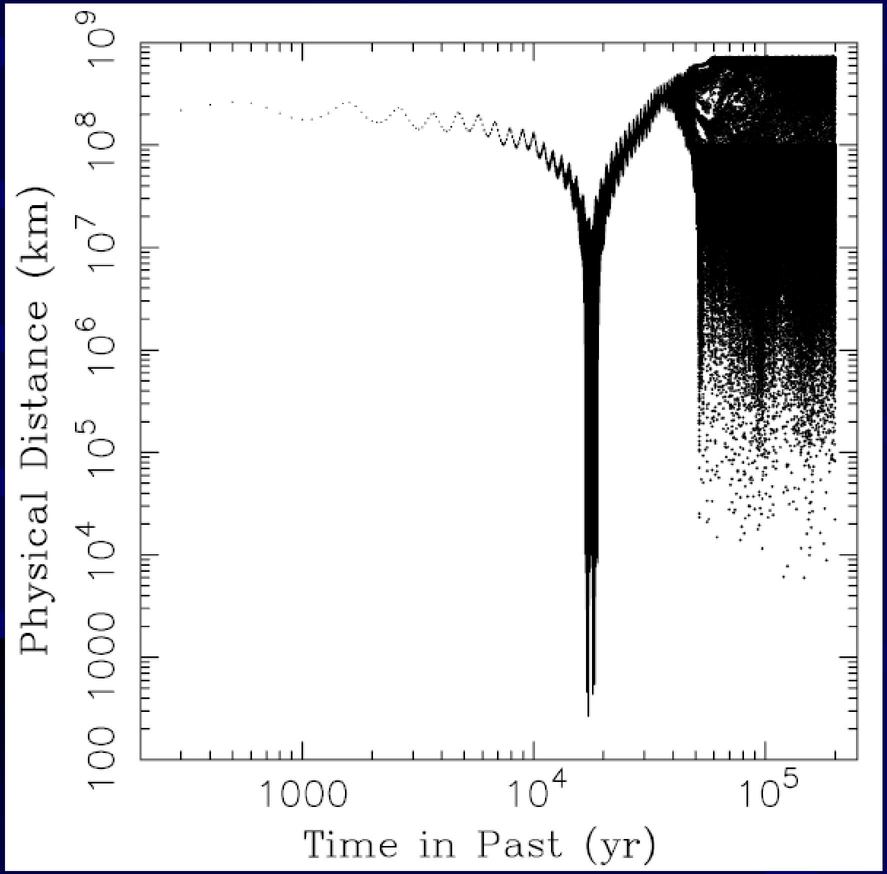


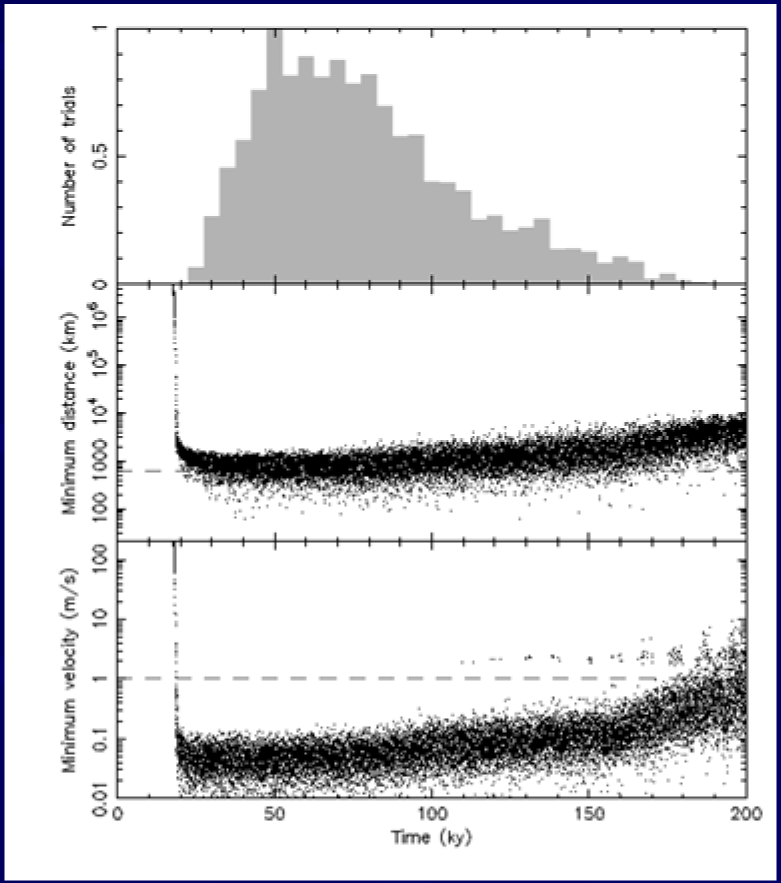
It is proposed to be due to the YORP tilt of spin axes of their parent bodies or the primaries toward the asymptotic states near obliquities 0 and 180° *(Pravec et al. 2012)*

Gentle separation in the asteroid's equatorial plane

Low relative velocities of asteroid pair components; low satellite's inclination in binaries

1) Relative velocities < 1 m/s, on an order of the escape velocity from parent body.





2) Orbital poles of most binary asteroids constant, i.e., the orbits not precessing on timescales of days to years, indicating a low inclination of the satellite's orbit - in the primary's equatorial plane.

Primaries’ rubble pile structure

Rubble pile primaries

1) The primary's "top shape" and equatorial ridge – "landsliding" and re-deposition of a large amount of regolith by tides from the secondary. *(Harris et al. 2009)*

Model of the primary of 1999 KW4 *(Ostro et al. 2006)*

2) Extremely low rigidity suggested from the apparent tidal-YORP equilibrium for 1996 FG3 *(Scheirich et al. 2014, submitted)*

Finally, we look at how the result converts to μQ, the product of the rigidity and quality factor. Using

$$\mu Q = \frac{4}{19}\frac{Q}{k}G\pi R_1^2\rho^2 \qquad (9)$$

from Goldreich and Sari (2009), we obtain $\mu Q = 1.3 \times 10^7$ Pa. While the upper limit

Secondaries probably rubble piles too

Secondaries above the Roche's limit for strenghtless satellites

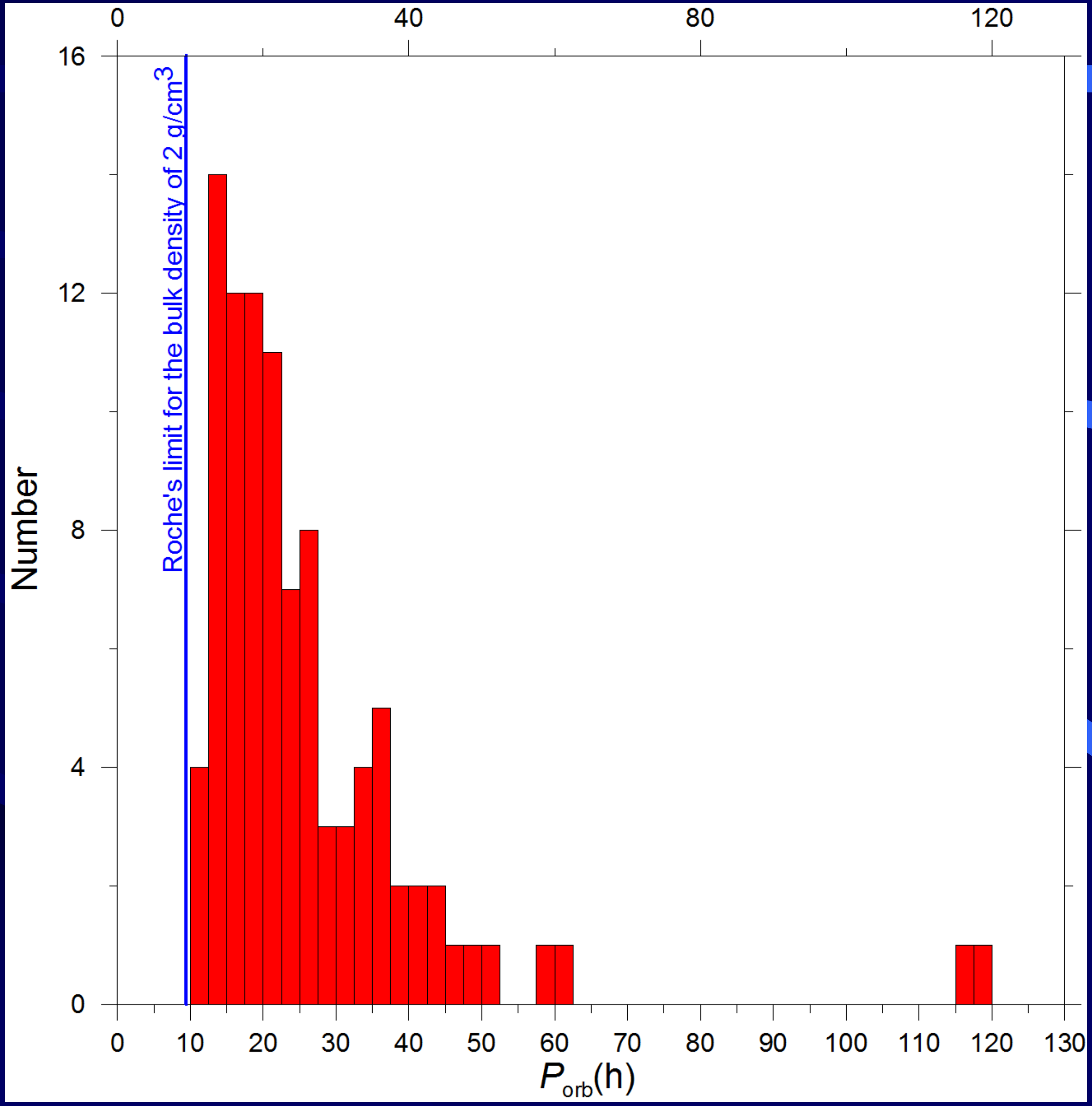
<u>Distances between components:</u>

Shortest P_{orb} ~ 11.9 h

- (65803) Didymos: 11.91 ± 0.02 h *(Pravec et al. 2006)*
- 2006 GY2: 11.7 ± 0.2 h *(Brooks 2006)*

Corresponds to a/R_1 = 3.0 ± 0.4. Consistent with the Roche's limit for strengthless satellites at a/R_1 = 2.54 (for same densities of the two bodies) that corresponds to P_{orb} ~ 9.5 h for the bulk density of 2 g/cm^3.

Alternatively, closer orbits may be unstable or short-living?



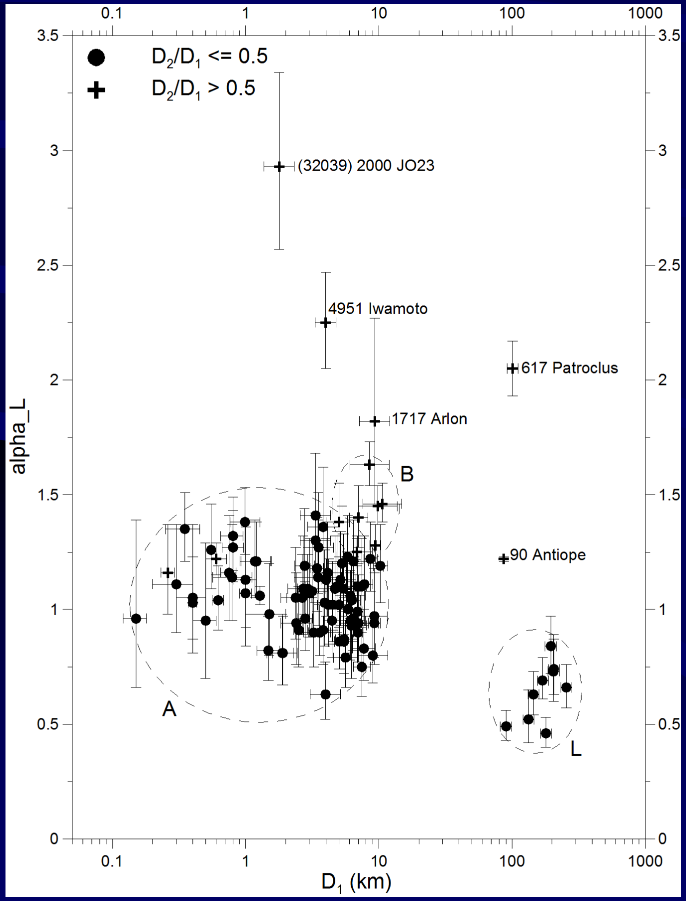
Anomalous cases – systems with super-critical angular momentum

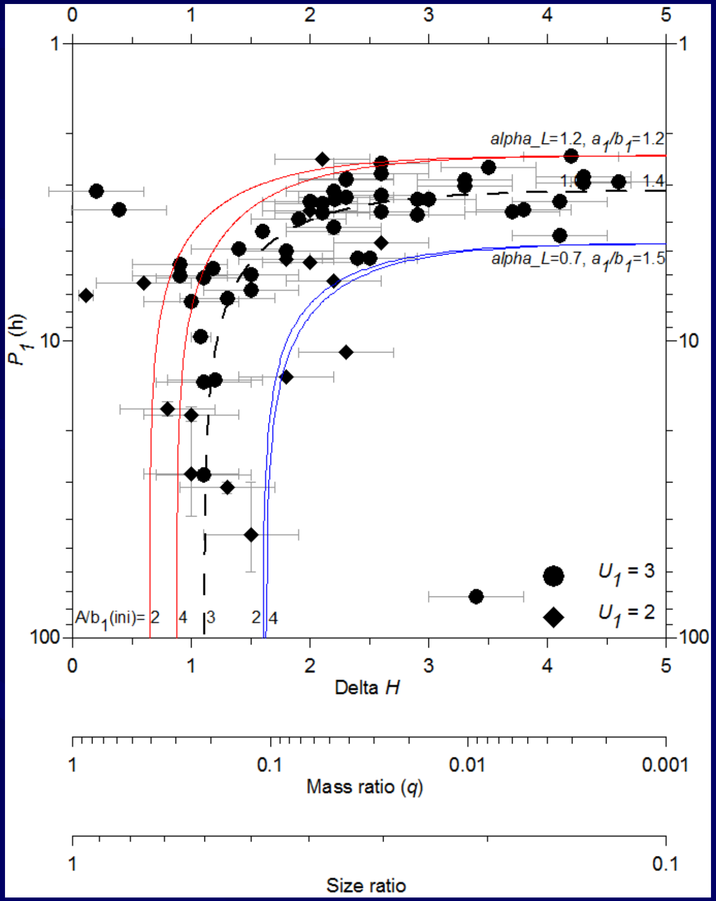
Systems with super-critical angular momentum

A few percent of systems, both bound and unbound, have an increased amount of angular momentum.

An explanation for the bound systems (32039) and (4951) proposed.

The three high-*q* asteroid pairs remain to be explained.

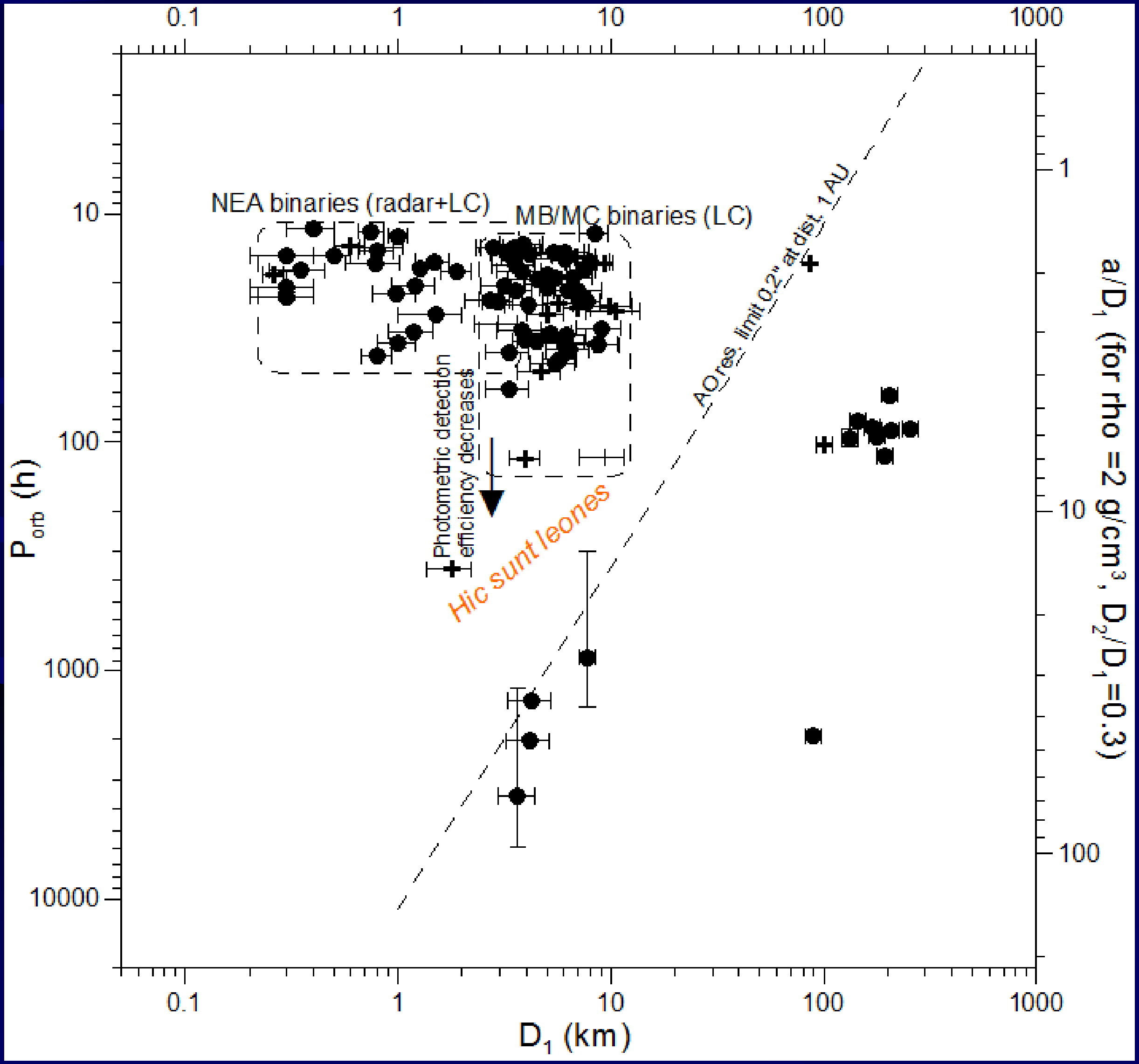




Medium-sized binaries

- prospects for their detection with *Gaia*

Binary population P_{orb} vs D_1



Binary fraction 15 ± 4 % among NEAs *(Pravec et al. 2006).*
Similar binary fraction among MBAs (up to D_1 = 10 km)

Data from *Pravec and Harris, Icarus,* 190 (2007) 250-253, updated.

Binary system's photocenter displacement

Photocenter displacement vector:

$$\mathbf{\Delta r} = \mathbf{r}[(1+q)^{-1} - (1+S)^{-1}], \tag{1}$$

where $\mathbf{r}$ is a projected radius vector, $q \equiv M_2/M_1$ is the mass ratio, and $S \equiv I_2/I_1$ is the brightness ratio between the components of the binary.

For spherical components with the same albedo and phase effect, it is $q = X^3$ and $S = X^2$ and

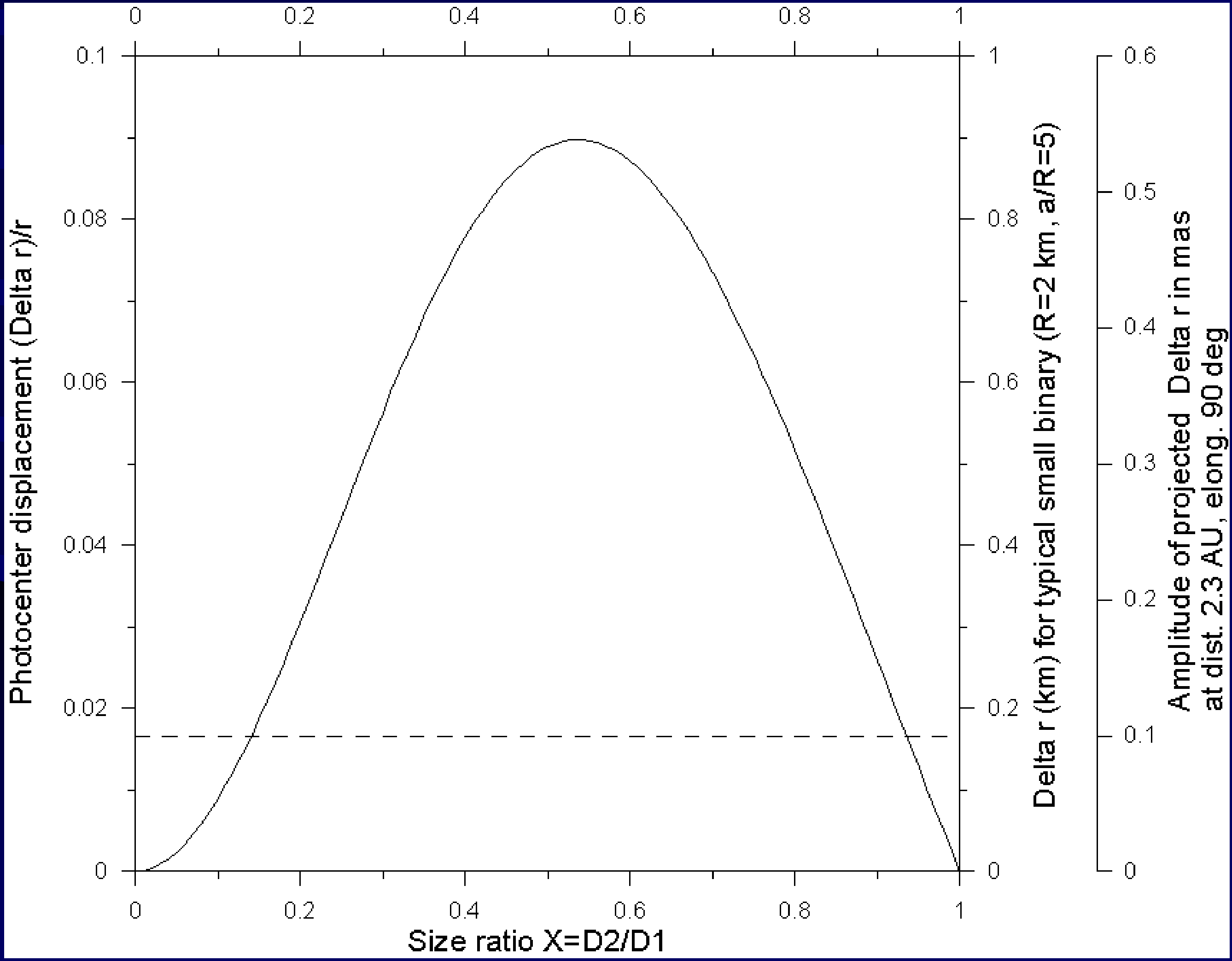
$$\mathbf{\Delta r} = \mathbf{r}[(1+X^3)^{-1} - (1+X^2)^{-1}], \tag{2}$$

where $X \equiv D_2/D_1$ is the size ratio between the binary components.

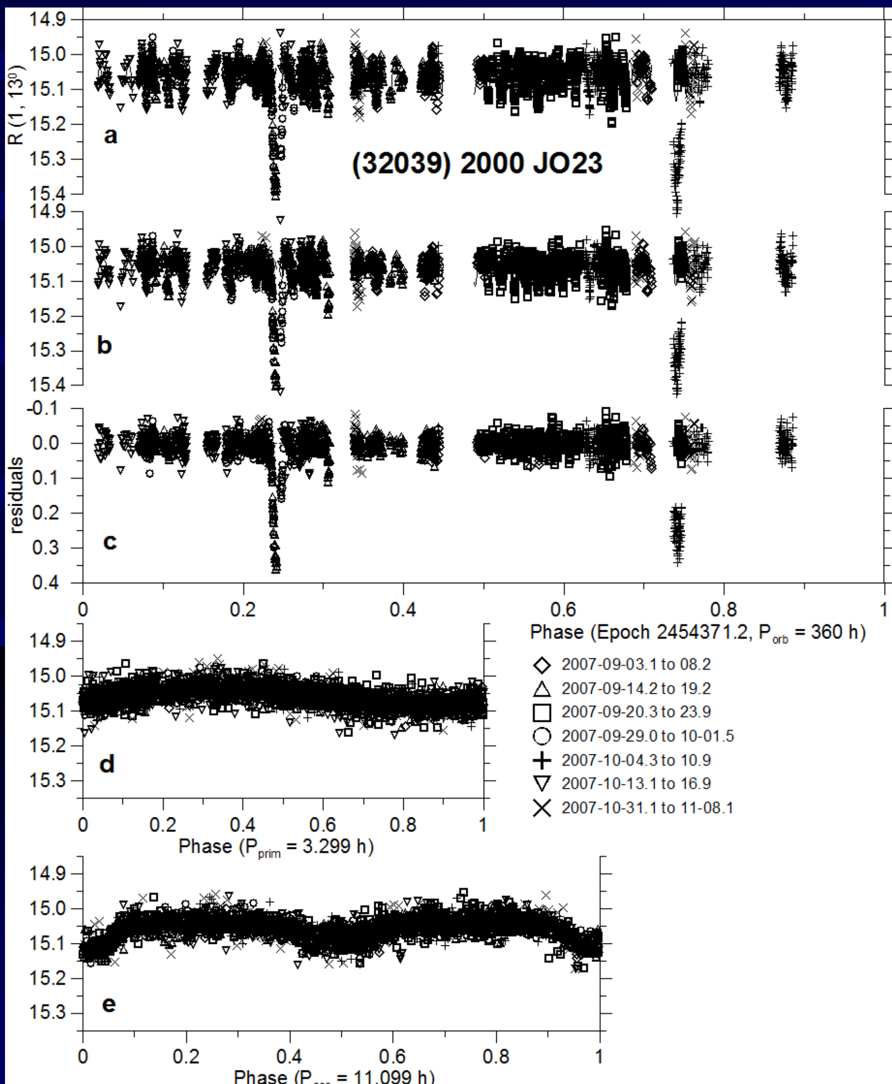
Degeneration – from an observed amplitude of the photocenter variation, we cannot separate the components' distance *r* and the size ratio *X*.

If P_{orb} is determined and D_1 estimated (from other observations), then the system's semimajor axis *r* can be constrained using The Third Kepler's Law, assuming a plausible range of bulk densities. Estimating of the size ratio *X* still largely ambiguous.

Photocenter displacement vs size ratio



(32039) 2000 JO23

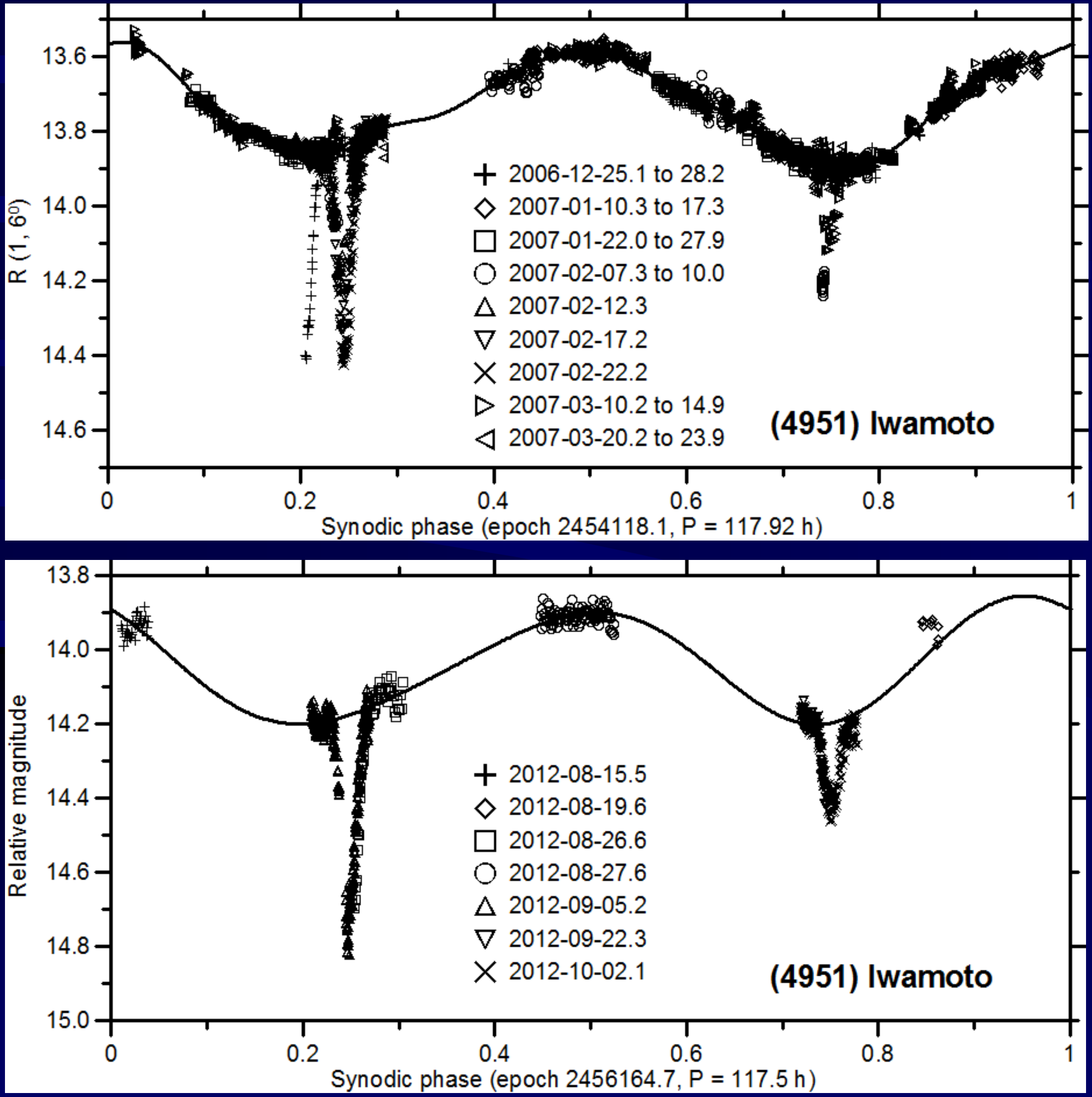


D_1 = 2 km
$D_2/D_1 \geq 0.58$
P_1 = 3.30 or 6.60 h
P_2 = 11.10 h
P_{orb} = 360 h
$a/R_1 \sim 32$
$\alpha_L \geq 2.3$ (super-critical)

Jacobson et al. (2014) proposed it formed as a result of the expanding singly synchronous mechanism. The extra angular momentum added by BYORP expanding the orbit. The secondary desynchronized as a result of the adiabatic invariance between the libration of the secondary and the mutual orbit – the system stranded at the wide separation. Observational test: Low *e*.

The other discussed mechanism –a direct outcome of rotational fission– does not explain the super-critical angular momentum.

(4951) Iwamoto



D_1 = 4.2 ± 0.6 km
D_2/D_1 = 0.88 ± 0.1
$P_1 = P_{orb}$ = 117.9 ± 0.2 h
(at least one component is synchronous)
a/R_1 ~ 17
α_L = 2.25 (unc. 25%)

Proposed explanation: Doubly synchronous system expanded by BYORP.

Conclusions

Asteroid systems, both bound and unbound, with primary sizes less than 15 km were formed by rotational fission of ‘rubble pile’ asteroids spun-up by YORP.

A tidal-BYORP dynamics can explain a couple observed anomalous bound systems with apparently super-critical amount of angular momentum.

A few high-mass ratio asteroid pairs (unbound systems) remain to be explained.