Binary systems among asteroid pairs*

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*From Pravec et al., 2019. Asteroid pairs: A complex picture. Icarus 333, 429-463

Asteroid pairs

We know since the work by *Vokrouhlický and Nesvorný (2008)* that there exists a population of pairs of asteroids residing on very similar heliocentric orbits. They showed that the asteroid pairs cannot be random, but they must be genetically related.

Since then, we advanced significantly with our understanding of asteroid pairs, and also asteroid clusters that appear also related to asteroid pairs. Our two recent papers:
Pravec et al., 2018. Asteroid clusters similar to asteroid pairs. Icarus 304, 110-126
Pravec et al., 2019. Asteroid pairs: A complex picture. Icarus 333, 429-463

One of the most interesting findings is that many fast-rotating primaries of asteroid pairs are actually binary systems. So, these asteroid pairs are in fact complex systems with both bound and unbound secondaries.

Asteroid pairs – identification and age estimation (1)

We find probable asteroid pairs by a statistical analysis of similarity of asteroid orbits in the 5-D space of mean orbital elements, using the method of *Pravec and Vokrouhlický (2009)*.

The distance *d* between two asteroid orbits:

d in 5-dimensional space of osculating orbital elements $(a, e, i, \varpi, \Omega)$ defined as a positive-definite quadratic form:

$$\left(\frac{d}{na}\right)^2 = k_a \left(\frac{\delta a}{a}\right)^2 + k_e(\delta e)^2 + k_i(\delta \sin i)^2 + k_\Omega(\delta\Omega)^2 + k_\varpi(\delta\varpi)^2 , \qquad (1)$$

where n and a is the mean motion and semimajor axis of either of the two asteroids and $(\delta a, \delta e, \delta \sin i, \delta\varpi, \delta\Omega)$ is the separation vector of their orbital elements. [1]

This distance is an approximate gauge for the relative velocity of the asteroids at close encounter. For most asteroid pairs, it is in the range from a few 10^{-1} to a few 10 m/s.

Asteroid pairs – identification and age estimation (2)

Candidate asteroid pairs found from the statistical analysis of proximity of asteroid heliocentric orbits –with a probability that they are a random orbital coincidence of two unrelated asteroids of < 10^{-2} typically– are confirmed with backward orbital integrations of their geometric and Yarkovsky clones. Times of clone encounters to within 5-10 R_{hill} and with relative velocities < 2 to 4 v_{esc} represent possible times of the separation of the two asteroids.

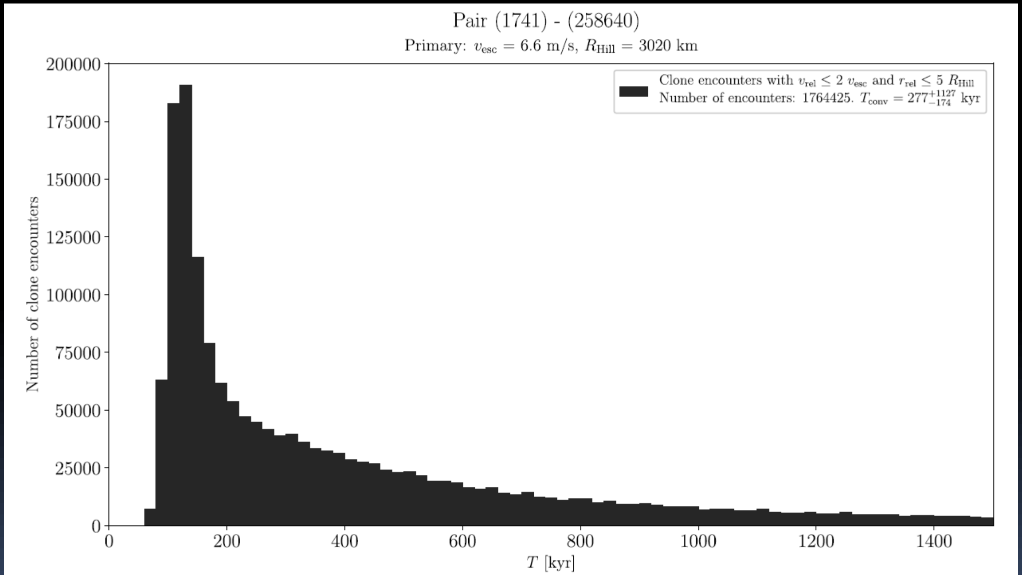
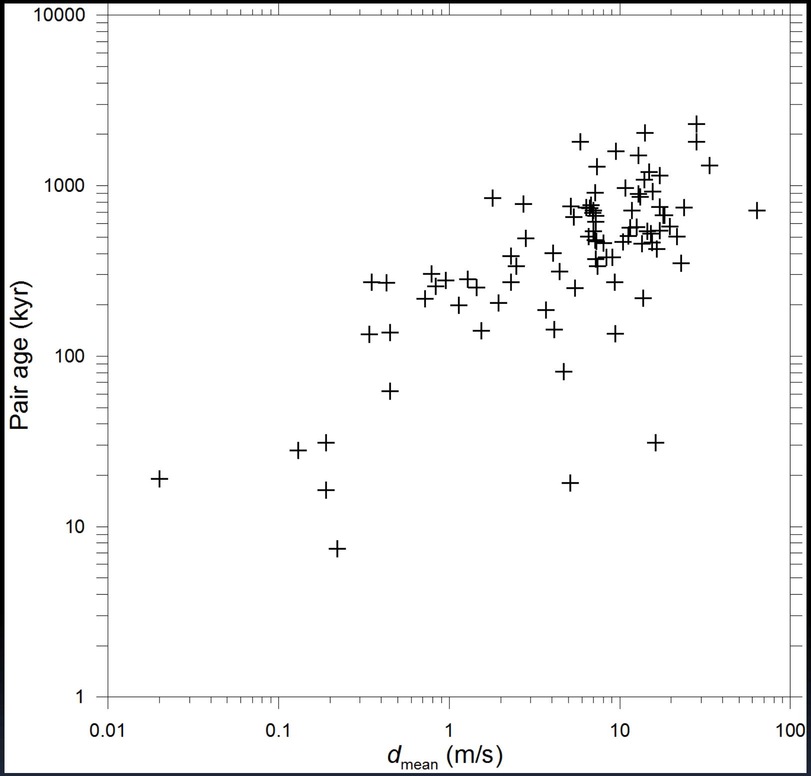


Fig. 2. Distribution of past times of close and slow primary–secondary clone encounters for the asteroid pair 1741–258640.

We take the median of the times of close and slow primary-secondary clone encounters as an estimate for the age of given asteroid pair.

Asteroid pairs – identification and age estimation (3)

The estimated pair age and the distance between the orbits of the pair members are correlated:

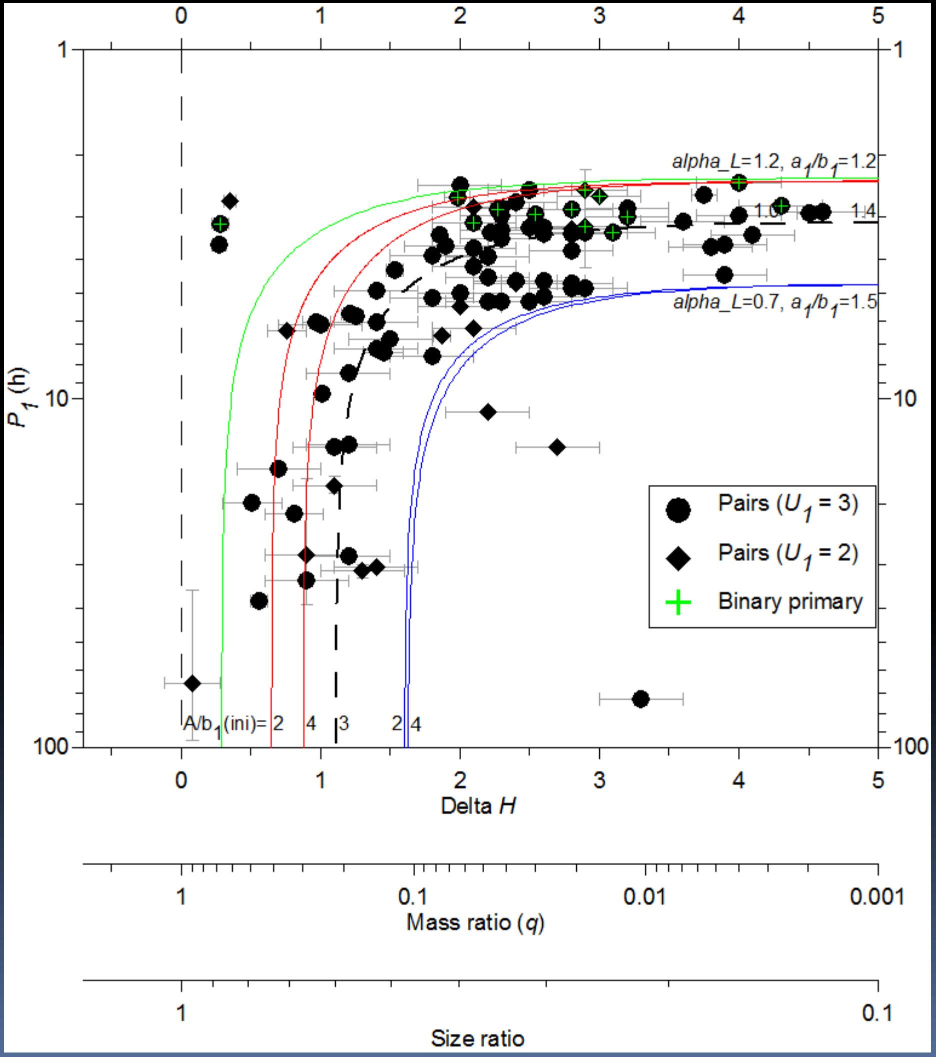


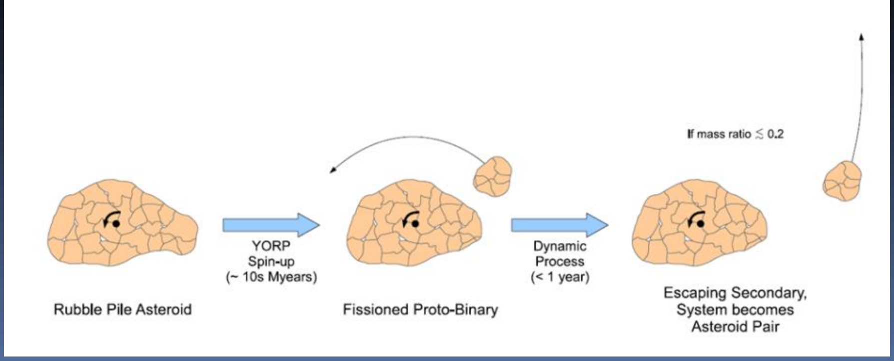
The orbits of pair members are dispersed in time, due to gravitational perturbations from major planets and large asteroids and due to different rates of their drift by the Yarkovsky effect. We can efficiently resolve asteroid pairs (in less-chaotic zones of the main belt and outside large collisional asteroid families) with d_{mean} <~30 m/s and younger than 1-2 Myr.

Asteroid pairs – our current sample

We know > 250 asteroid pairs as of today. In our recent paper Pravec et al. (2019), we studied 93 of them. 86 of the 93 have the primary rotation periods and mass ratios in the range predicted by the theory of their formation by rotational fission of (effectively) cohesionless rubble pile parent asteroids spun up to the critical rotation by the YORP effect *(Scheeres 2007, Pravec et al. 2010)*.

It is by far a predominant formation mechanism for asteroid pairs.





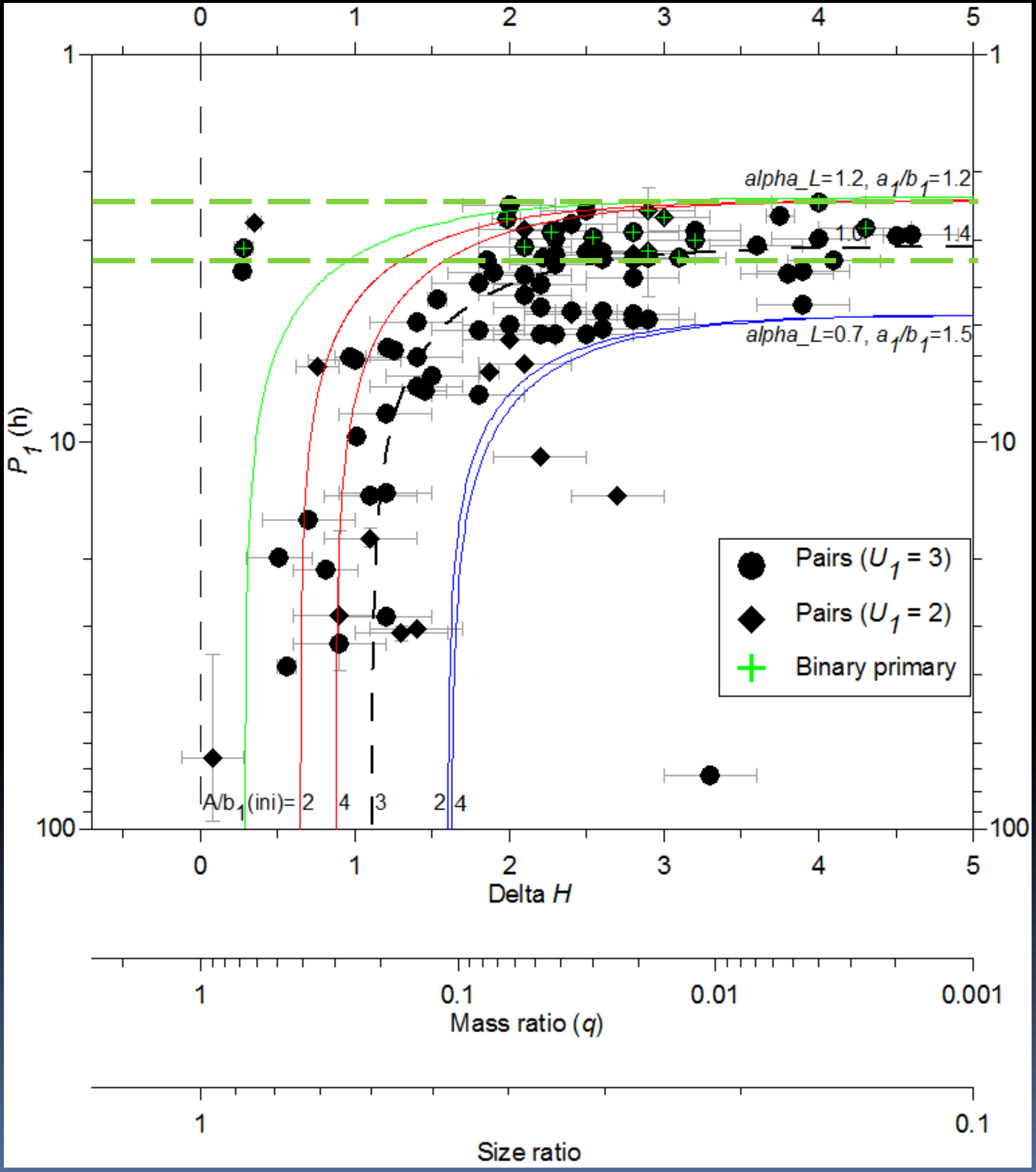
Asteroid pairs with binary primaries

We found that the primaries of 13 of the 93 studied pairs are actually binary asteroids.

They concentrate in the narrow range $P_1 < 3.4$ h.

Of the 34 asteroid pairs with $P_1 < 3.4$ h, the 13 is a fraction of 38%. The real fraction of binary systems among these fastest-rotating asteroid pair primaries is higher, probably at least 50%.

It may be comparable to the binary fraction among the fastest rotating near-Earth asteroids larger than 0.3 km that is (66^{+10}_{-12})% *(Pravec et al. 2006)*.



The 13 asteroid pairs with binary primaries

Asteroid pair primaries satellites.

Asteroid 1	Asteroid 2	$D_{1,p}$ (km)	$\frac{D_2}{D_{1,p}}$	$\frac{D_{1,s}}{D_{1,p}}$	$\frac{a_{orb}}{D_{1,p}}$	e	$P_{1,p}$ (h)	P_{orb} (h)	$P_{1,s}$ (h)	α_L	$A_{1,p}$ (mag)	$A_{1,s}$ (mag)	SolPh (°)	$\frac{a_{1,p}}{b_{1,p}}$	$\frac{a_{1,s}}{b_{1,s}}$
(3749) Balam	(312497) 2009 BR60	4.1	0.16	0.46	3.1	0.03–0.08	2.8049167	33.38	33.39	(1.31)	0.11	0.04	8	1.11	1.20
(3749) Balam	(312497) 2009 BR60	4.1	0.16	0.24	55	0.3–0.8	2.8049167	2600		(1.29)	0.11		8	1.11	
(6369) 1983 UC	(510132) 2010 UY57	3.3	0.17	0.37	3.4	0	2.39712	39.80	39.80	1.30	0.06	0.06	5	1.06	1.53
(8306) Shoko	2011 SR158	2.4	0.27	≥ 0.40	3.3	0	3.35015	36.20	36.20	(1.19)	0.13	0.05	6	1.14	1.28
(9783) Tensho-kan	(348018) 2003 SF334	5.1	0.24	0.24	2.8	0	3.0108	29.5663		0.95	0.19		3	1.19	
(10123) Fideöja	(117306) 2004 VF21	3.2	0.37	0.36	4.3	0	2.8662	56.46		1.16	0.08		4	1.08	
(21436) Chaoyichi	(334916) 2003 YK39	1.9	0.29	0.36	5.5	0.16–0.22	2.8655	81.19		1.21	0.10		13	1.09	
(25021) Nischaykumar	(453818) 2011 SJ109	2.0	0.28	0.28	2.4	0	2.5344	23.4954	23.50	1.09	0.07	0.04	18	1.05	1.46
(26416) 1999 XM84	(214954) 2007 WO58	3.4	0.33	≥ 0.25	2.2	< 0.08	2.9660	20.7805	20.78	0.97	0.07	0.02	11	1.06	1.24
(26420) 1999 XL103	2012 TS209	1.2	0.29	≥ 0.34	(3.9)		3.2	(47.80)		(1.14)	0.09		10	1.08	
(43008) 1999 UD31	(441549) 2008 TM68	1.8	0.44	≥ 0.35	1.9	0	2.64138	16.745	16.7	1.17	0.09	0.07	6	1.09	1.53
(44620) 1999 RS43	(295745) 2008 UH98	1.9	0.41	0.39	3.1	< 0.13	3.1393	33.6455	33.2	1.11	0.11	0.04	7	1.11	1.26
(46829) McMahon	2014 VR4	2.5	0.28	0.40	2.0		2.6236	16.833		1.19	0.11		2	1.12	
(80218) 1999 VO123	(213471) 2002 ES90	0.9	0.92	0.32	3.1	0	3.1451	33.10	33.4	1.02	0.20	0.04	3	1.21	1.52

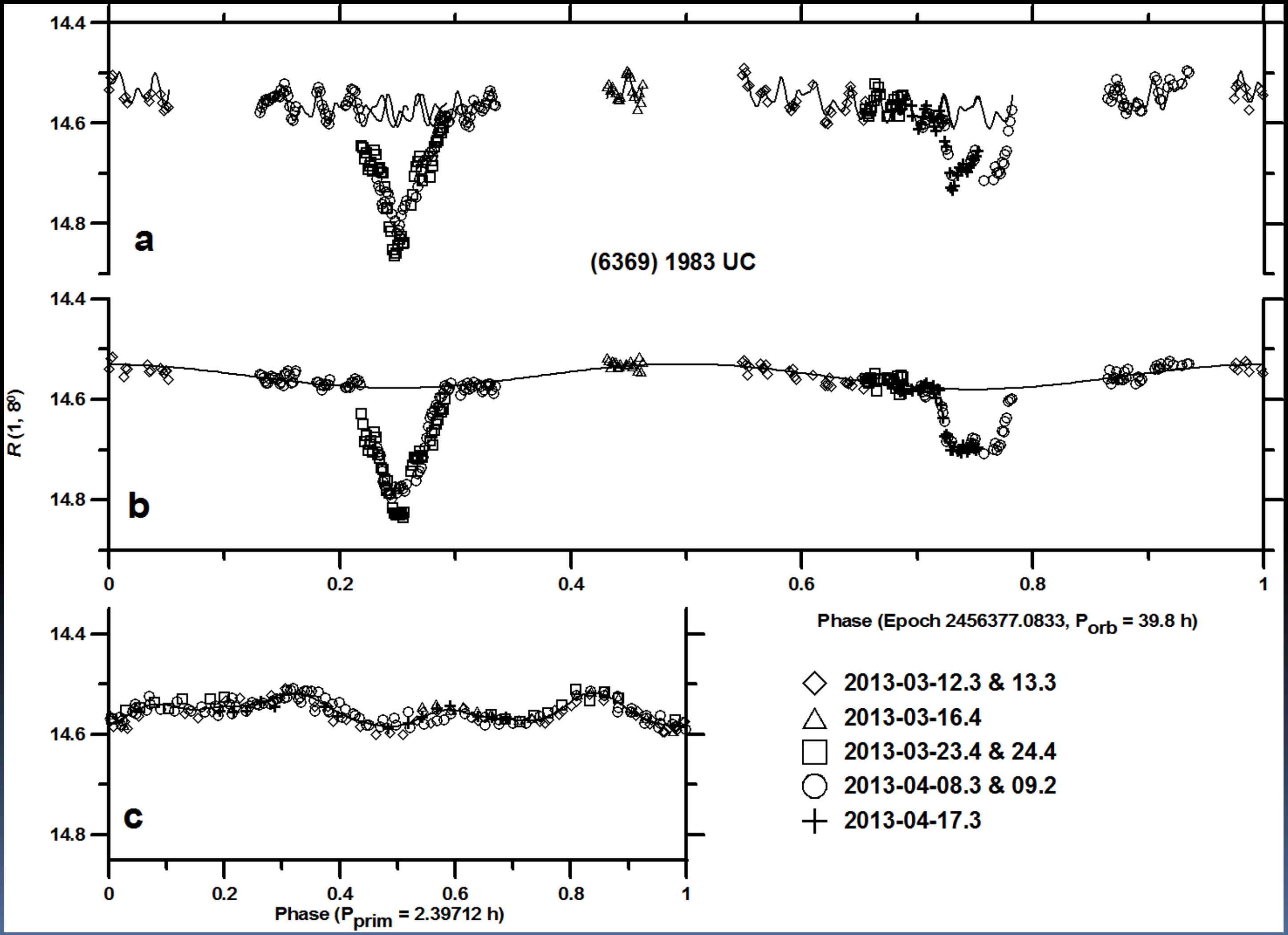
The binary systems among asteroid pair primaries share also other common features with known near-Earth and small main belt binary asteroids.

- The bound secondaries are relatively small with $D_{1,s}/D_{1,p} < 0.5$.
- The normalized total angular momentum content is close to critical.
- The primaries are nearly spheroidal with $a_{1,p}/b_{1,p} \leq 1.2$.
- The secondaries have low to moderate equatorial elongations with $a_{1,s}/b_{1,s} \leq 1.5$.
- The orbital periods of the bound secondaries are in the realm of tens of hours.

It is also notable that, with an exception of (3749) Balam and (21436) Chayoichi, the orbits and rotations of the bound secondaries are relaxed with eccentricities close to 0 and synchronous spin states.

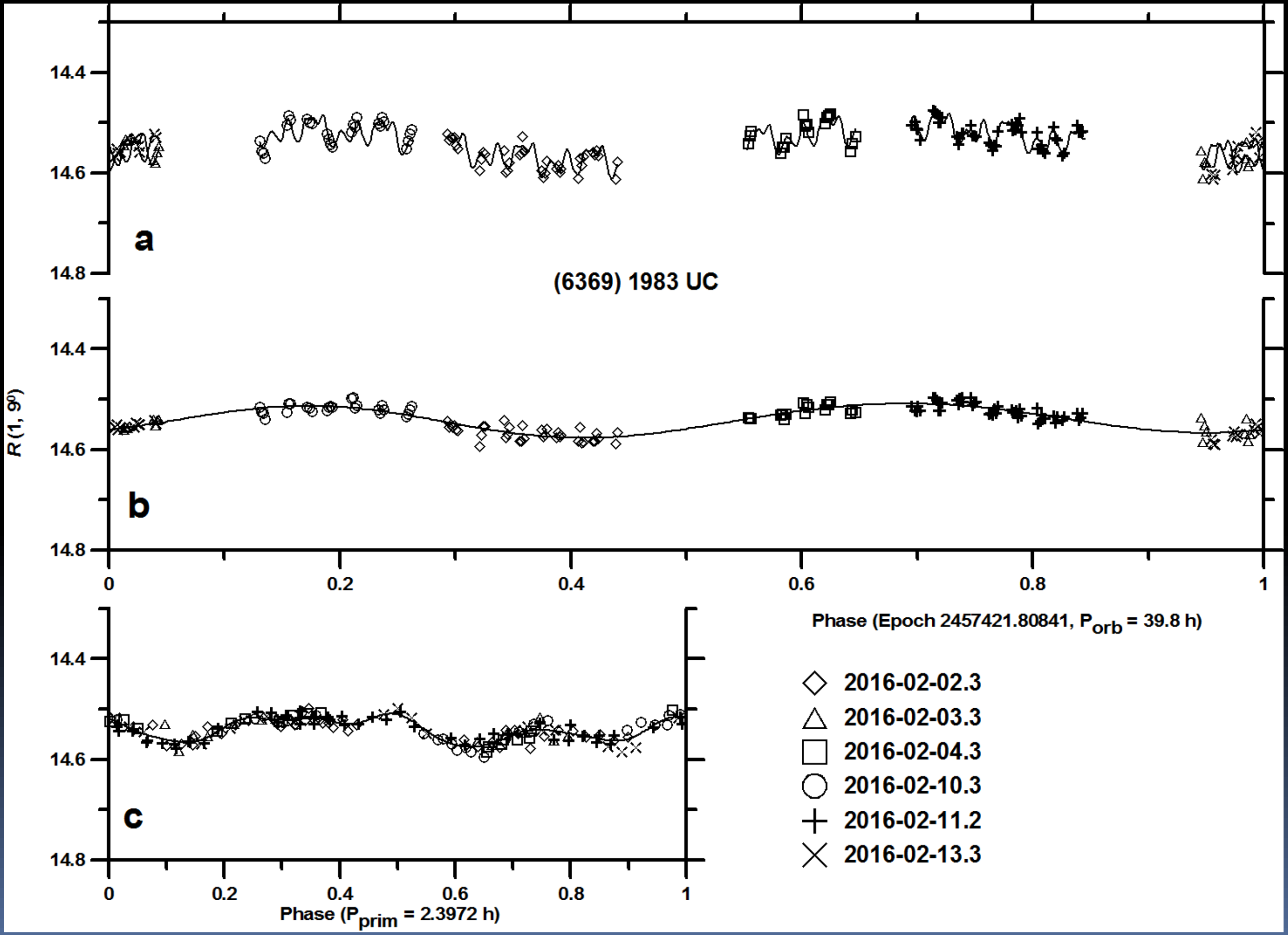
Paired binary asteroid (6369) 1983 UC – 2013 data

Our discovery observations with the 1.54-m telescope from La Silla in March-April 2013:



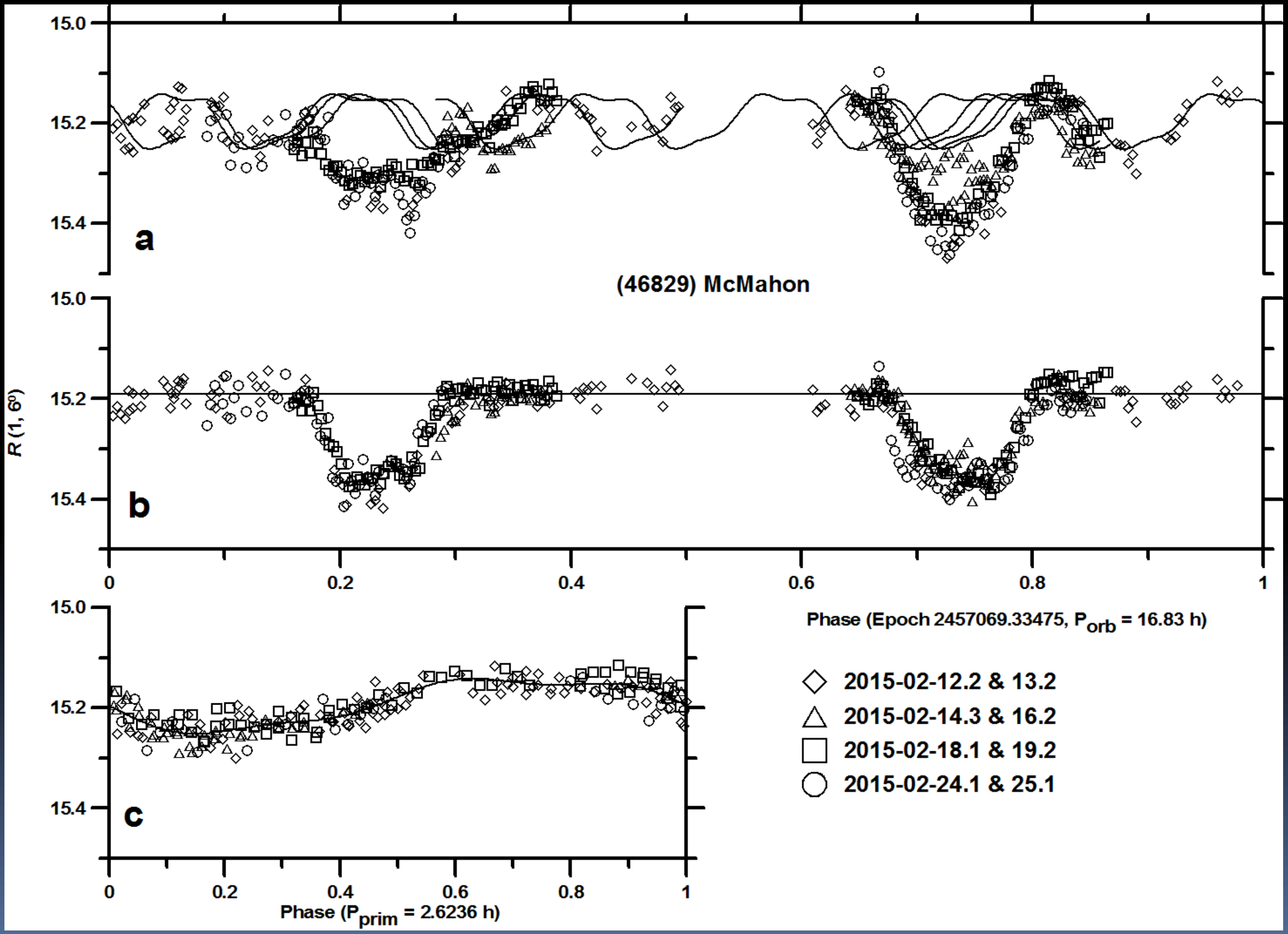
Paired binary asteroid (6369) 1983 UC – 2016 data

Our follow-up observations in February 2016. The system was outside event geometry (both from Earth and Sun):



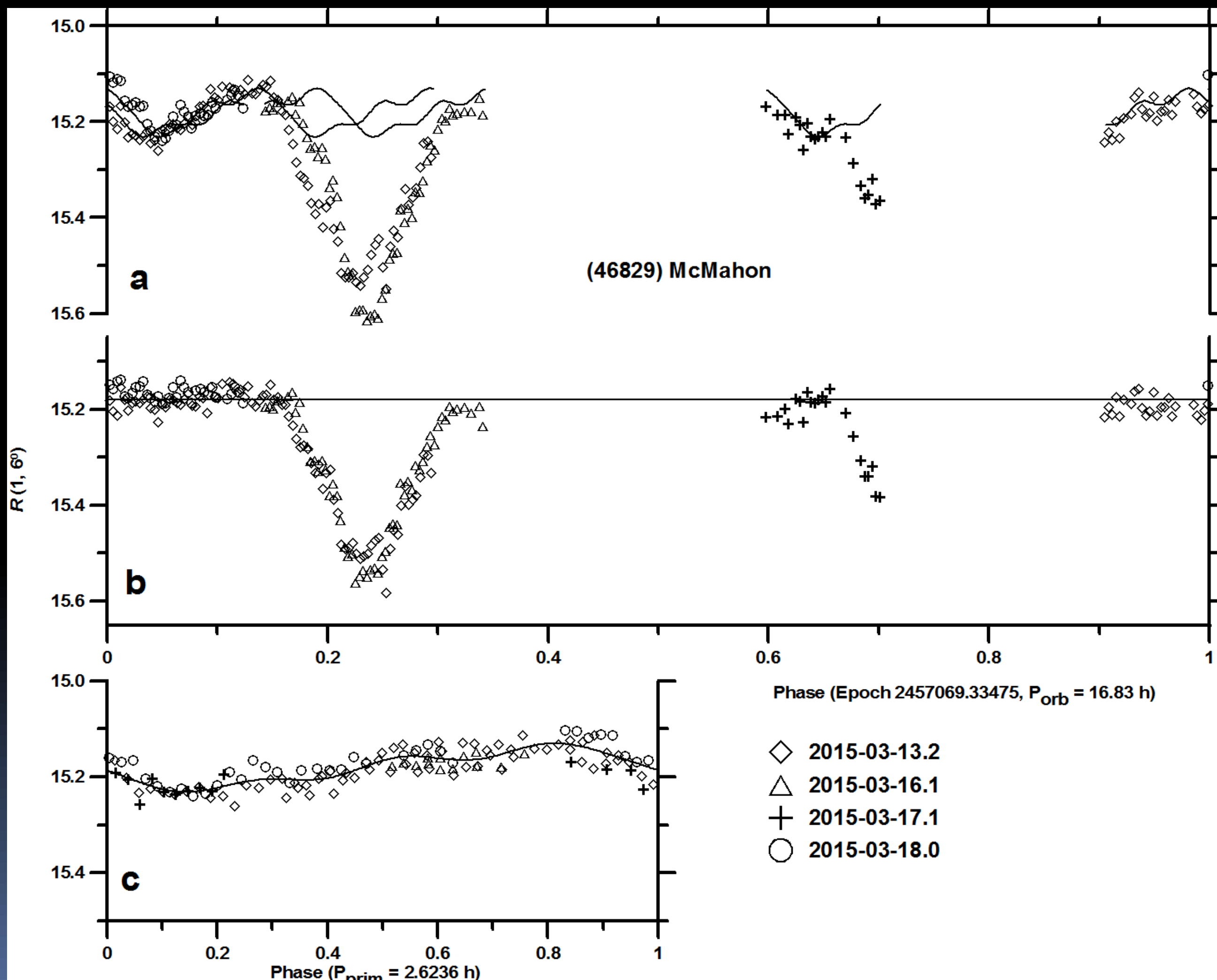
Paired binary asteroid (46829) McMahon – 2015a data

Our discovery observations with the 1.54-m telescope from La Silla in February 2015:



Paired binary asteroid (46829) McMahon – 2015b data

Our follow-up observations in March 2015:



Formation theories for paired binary asteroids

Asteroid pairs having both bound, orbiting and unbound, escaped secondaries might be outcomes of

1. Secondary fission process *(Jacobson and Scheeres 2011)*
2. Cascade, repeated fission of the primary (cf. the talk by Petr Fatka)

Jacobson and Scheeres (2011) proposed that there could occur a process called “secondary fission” in asteroid pairs: a rotational fission of the secondary induced via spin–orbit coupling between the primary and the secondary and occurring during the chaotic binary stage (i.e., before the secondary escapes from the system and it becomes an asteroid pair).

In *Pravec et al. (2018)*, we proposed that the secondary fission process was involved in formation of young asteroid clusters.

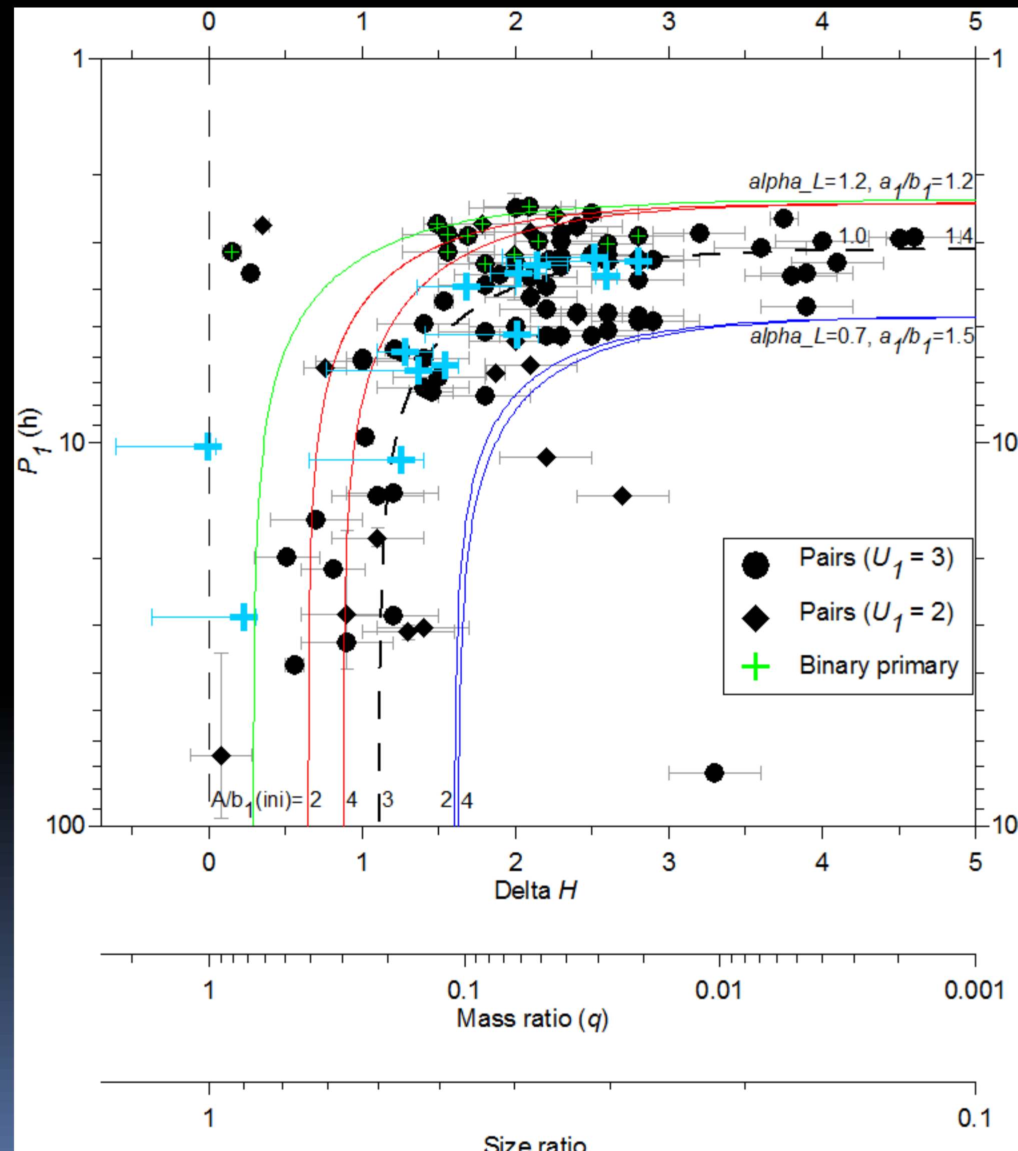
We suspect that the asteroid pairs with binary primaries could be “failed asteroid clusters” where only one of the two formed secondaries escaped.

Asteroid pairs with binary primaries – the “failed asteroid cluster” hypothesis

We corrected the mass ratios and primary rotation periods of the 13 pairs with binary primaries for what they would be if the bound orbiting secondary also escaped and the system became a real asteroid cluster.

The “corrected” data for asteroid pairs with binary primaries have the same range of mass ratios, but they rotate substantially faster than the primaries of the 13 known asteroid clusters.

It suggests that there is involved a mechanism that stabilizes secondary orbits around the fastest rotating primaries with $P_1 < 3.4$ h, but not around somewhat slower rotating ones.



Asteroid pairs with binary primaries – the cascade primary fission hypothesis

We imagine following possible scenario (alternative to the proposed "secondary fission" mechanism) for formation of more than one secondary:

There was formed a satellite (orbiting secondary) of the primary in a spin fission event at an earlier time in the past, with the primary rotating sub-critically after the satellite formation. Then the primary was spun up by YORP to the critical spin rate again and underwent another fission event. The new secondary started chaotically orbiting the primary and it gravitationally interacted with both the primary and the older secondary. One of the two secondaries was then ejected from the system, becoming the unbound secondary (the smaller member of asteroid pair), and the other secondary's orbit around the primary was stabilized, so the system became an asteroid pair with binary primary.

In the 4 known asteroid clusters with cascade disruption events, the last events occurred probably between ~70 and ~300 kyr ago. (See the talk by Petr Fatka.) For comparison, the 13 asteroid pairs with binary primaries are between ~30 and ~900 kyr old.

Concluding remarks

Were "ordinary" binary asteroids that we observe in large numbers in the main belt (as well as near Earth) also paired binaries in the (more distant) past? They have very similar properties, except for that the ordinary ("non-paired") binary asteroids have a tail of the distribution of primary periods to longer values: 29% of observed ordinary binaries have P_1 > 3.4 h; they could be just older, more evolved systems (by tides or BYORP).

How was the outer (smaller) satellite of the triple system of (3749) Balam formed? Is it an old satellite that was formed a long time ago and survived the recent events in the system? Note that the pair 3749-312497 is ~400 kyr old. Also notable is that the close, larger secondary is not fully relaxed yet, it has an eccentric (e = 0.03 – 0.07, 3-σ range) and inclined/precessing orbit, but it is synchronous.

The youngest known paired binary is (21436) Chaoyichi with estimated age about 30 kyr. Its bound secondary has e = 0.19 ± 0.03 (3-σ). (The secondary's rotation has not been constrained – it seems not very elongated.) All other paired binaries with synchronous satellites in circular orbits have ages >~140 kyr. The data may place constraints on relaxation times in such small a few-km diameter asteroid binaries.

Thank you!