The Danish 1.54-m telescope on La Silla and the NEOSource project

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The Danish 1.54-m telescope

A dedicated photometric telescope.

Owner: Niels Bohr Institute (NBI), Copenhagen University

Operated collaboratively by the NBI and the AI AS CR (plus the groups from MFF UK and PřF MU) – The present agreement is for October 2012 to September 2018.

The Danish 1.54-m telescope

In 2012 the telescope was refurbished and a new control system was installed.

The author of the new control system is ProjectSoft HK.

The telescope upgrade was funded by the Academy of Sciences of the Czech Republic (with contributions from PřF MU Brno and MFF UK Prague) for our major project of studies of near-Earth asteroid properties, and for the supplementary projects of stellar photometry in support of Gaia and of Magellanic Clouds.

The Danish 1.54-m telescope

<u>The telescope is fully remotely controlled</u> – observations are done from our workplace here, no need for a local observer or technician at night.

ESO provides a few things: Electricity, daily LN2 refilling, internet connection.

We pay nightly fee to ESO for their service. Occasional technical interventions (typically one per 1-2 months) are paid per work person-hours.

DK154 parameters and capabilities

DFOSC + CCD camera in the Cassegrain focus:

2k*2k, pixel scale 0.40", FOV 13'

Filters (in active use):
Johnson-Cousins (Bessell) UBVRI,
Stromgren ubvy, g2, Gunn z, Hβ.

Gain: 0.25 e⁻/ADU.
Dynamical range 19.4 bit (linearity to 700 kADU).
Readout noise 4.5 e⁻
Full CCD readout time: 22 seconds.
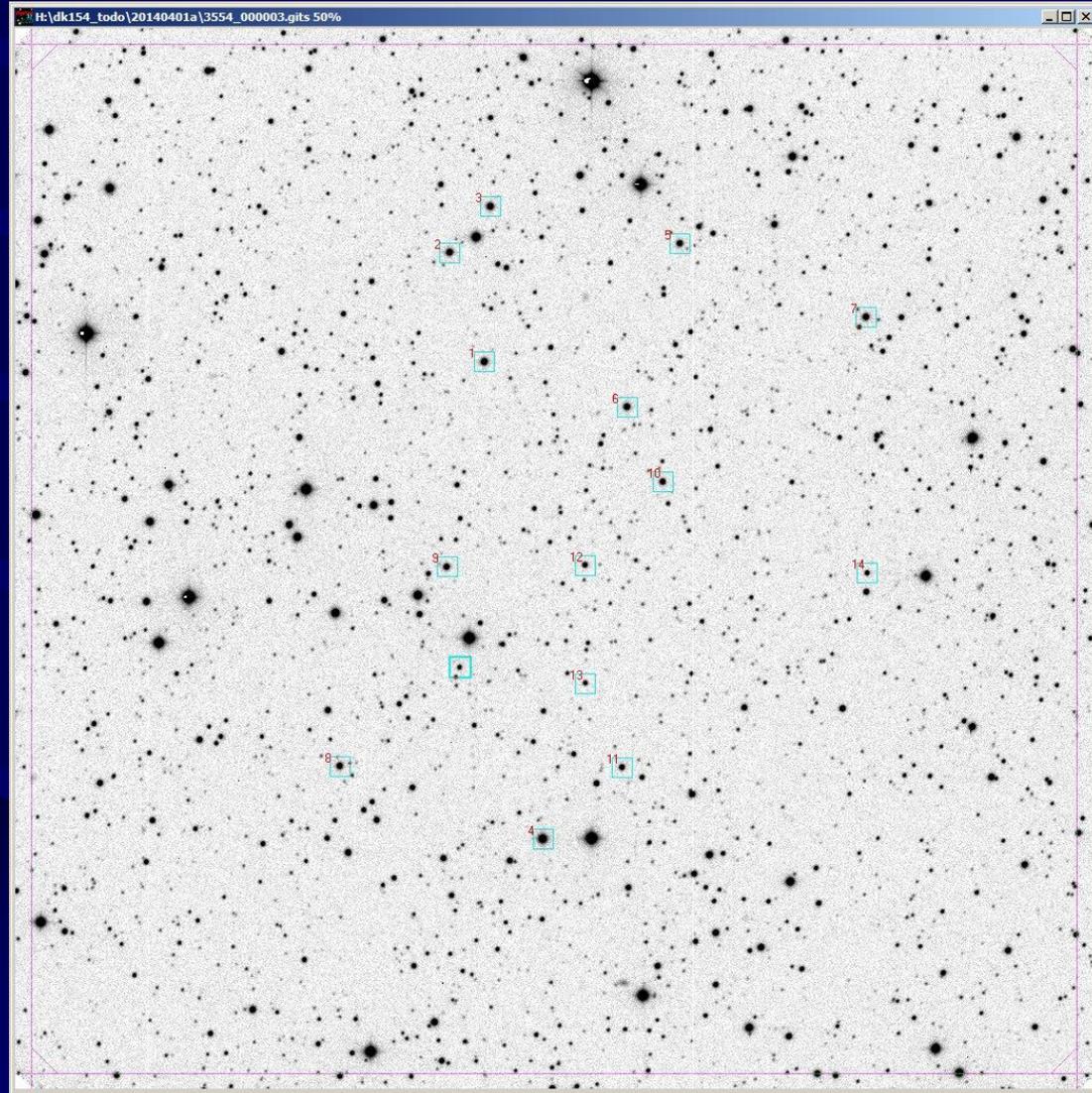
DK154 parameters and capabilities

Limiting magnitude (3-min integration):
V_{lim} = 18.5 at SNR =100
V_{lim} = 20.0 at SNR =30

Typical seeing: <1" (median 0.8-0.9").

Fraction of usable night time (during our season October-April):
- Only 4% of nights have been totally lost due to bad weather.
- The net time loss has been 10% for weather and 4% for technical and other reasons.

DK154 control system

Highly automated operation.

Safety system – takes care of the telescope and dome in a case of
- bad weather
- human intrusion to the dome
- loss of remote observer's connection

The core is based on industrial components and solutions.

Many things are backed up, doubled (some even tripled), to eliminate as many bottle necks as possible.

Not robotic (yet).
Some things are script-controlled (under development).
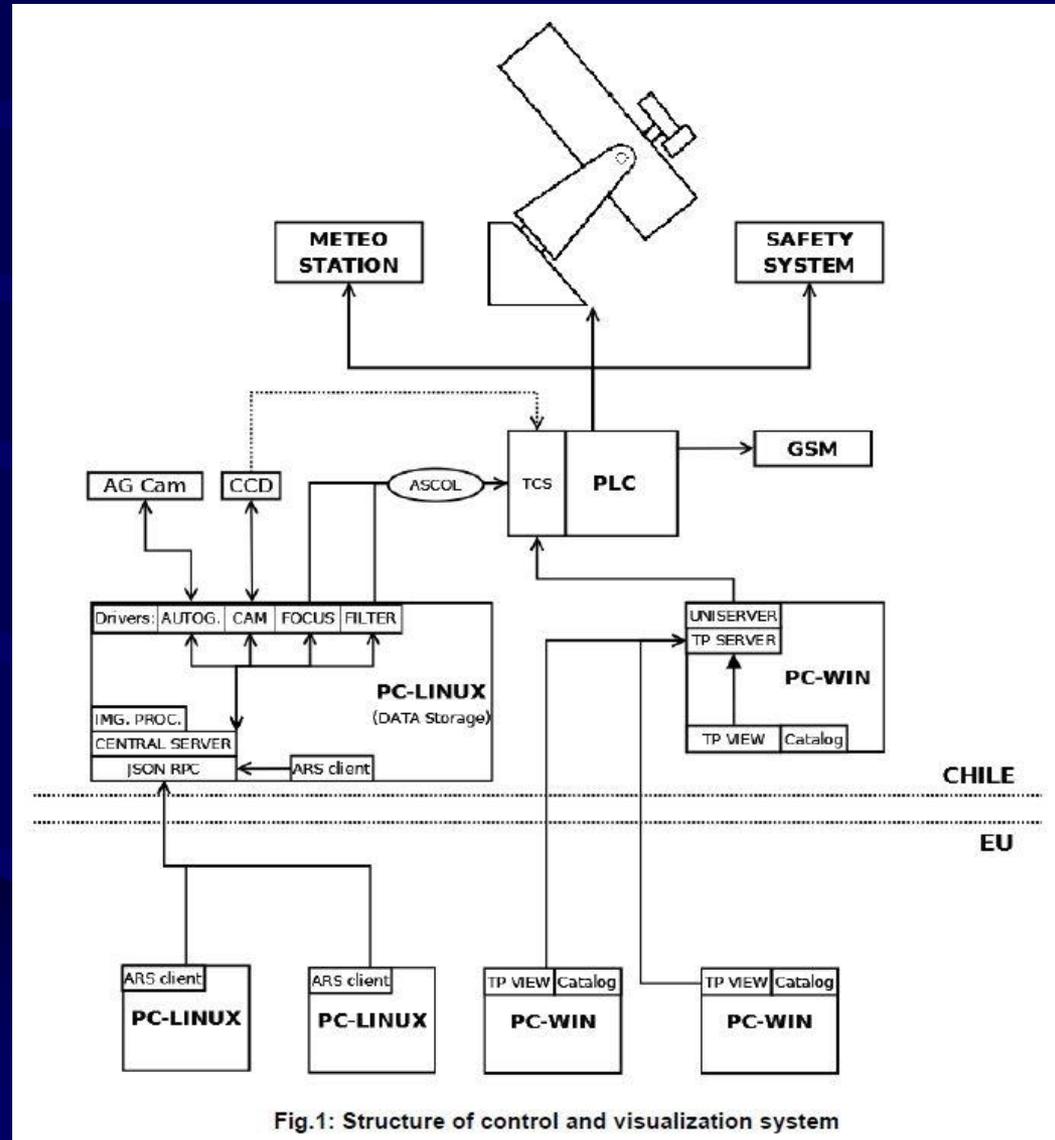
Fig.1: Structure of control and visualization system

DK154 remote observations

Observer connects to the telescope via ESO_Santiago_VPN.

The Telescope Control System (TCS) and image acquisition clients run on local computer here and they communicate with the TCS server over the internet.

Images obtained are transferred to our dk154-data storage server in Ondřejov in near-real time (typically in 30 seconds after completing readout).

Direct connection and control is hampered/prohibited – there is the latency between La Silla and Europe (300 ms) that limits a use of non-parallelized communication.
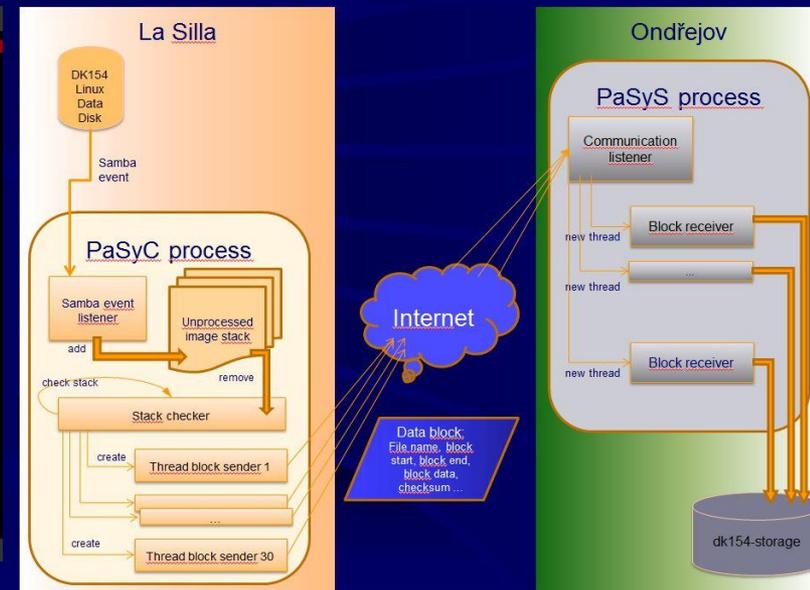
DK154 remote observations

Observations partly automated
- automated image series acquisition
- automated focusing, autoguiding
- scripting (under development) – automatic field sequencing, flat field frames acquisition

Not really robotic:
Observer cannot sleep
(at least not for a longer
time ☺).

Science projects running at DK154

Danish, Czech, and Chilean time

DK154 collaborative use

<u>Danish season</u>, 6 months from mid-April to mid-October (minus 10% given to Chileans)
Main project:
MiNDSTEp (Microlensing Network for the Detection of Small Terrestrial Exoplanets)
www.mindstep-science.org

<u>Czech season</u>, the other 6 months (minus 10% given to Chileans)
NEOSource (PI P. Pravec, Co-PI D. Vokrouhlický) – 82 nights per year
Gaia Support (PI P. Koubský)
LSMC Prague (PI M. Wolf)
LSMC Brno (PI M. Zejda)
- 27 nights/year each.

<u>Chilean observations</u>
ESO's contractual obligations to the Chilean astronomy: 10% of nights offered to Chileans, i.e., 36 nights/year. They mostly observe transits of expolanets.

NEOSource project

Study of non-gravitational asteroid evolution processes via photometric observations

NEOSource project

Study of non-gravitational asteroid evolution processes via photometric observations
PI Petr Pravec, Co-PI David Vokrouhlický
Supported by GAČR, grant P209/12/0229.

2012 October – 2016 December, observations on 82 nights/year with the 1.54-m telescope at La Silla.

The effects we study can be detected with long-term monitoring, hence the need of a dedicated telescope.

A look ahead:
Recently we have submitted a proposal to the EC Horizon 2020-PROTEC-2-NEOs call. We have formed a consortium of NEO research groups from 10+ European countries, called *The European NEO Science Network.* The project will run during 2015-2018. Will provide a deep understanding of NEO properties using several observational techniques and extensive modeling. Will also characterize NEO targets for spacecraft missions, both human and robotic.

NEOSource project - Tasks

1. BYORP effect in near-Earth <u>binary asteroids</u>

2. Multiplicity of <u>asteroid pairs</u>

3. Spin vectors of <u>asteroid pairs</u>

4. Size ratios of <u>asteroid pairs</u> with small nominal astrometric dH

5. <u>YORP effect in NEAs</u>, enlarging the sample

6. Spin vectors in the <u>Datura collisional family</u>

7. Survey for <u>tumblers among super-fast rotating NEAs</u>

8. Spins of the largest members of <u>asteroid clusters</u>/mini-families

9. Spin rates and vectors of <u>asteroids with detected Yarkovsky effect</u>

Binary systems
among NEAs and small MBAs

Improving their understanding (Task 1, detection of the BYORP effect)

and relation with other asteroidal phenomena (Task 2, multiplicity of paired asteroids)

Binary near-Earth asteroid (88710) 2001 SL9
- candidate for BYORP effect detection (Task 1)
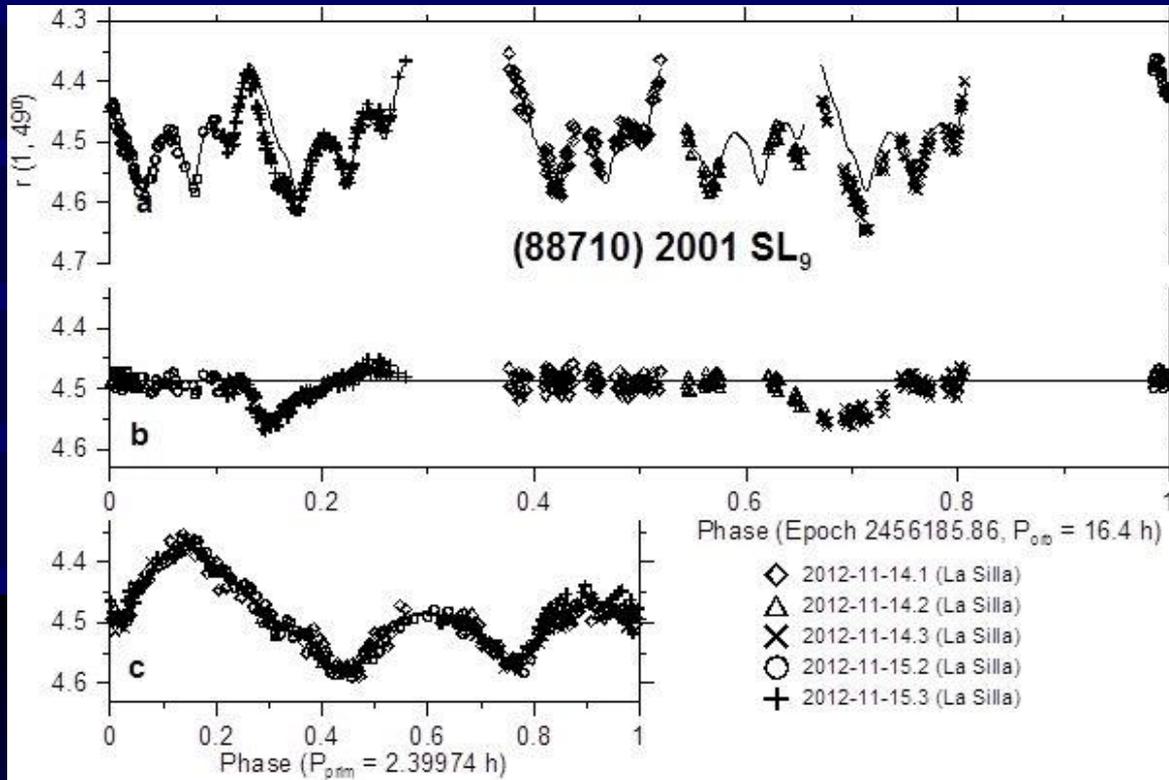
Photometric errors
0.013 mag

Derivable parameters: P_1, P_{orb}, (P_2), D_2/D_1, a_1/b_1, (a_2/b_2) and finally (with long-arc observations) L_p, B_p, e
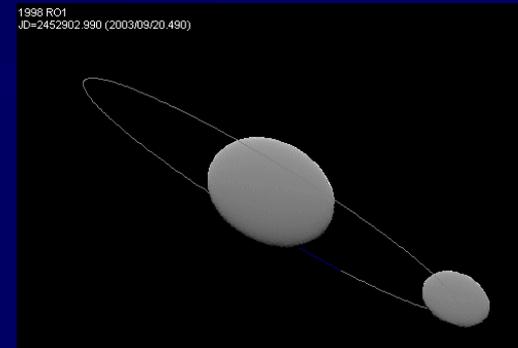
Binary paired asteroid (10123) Fideoja
(Task 2)
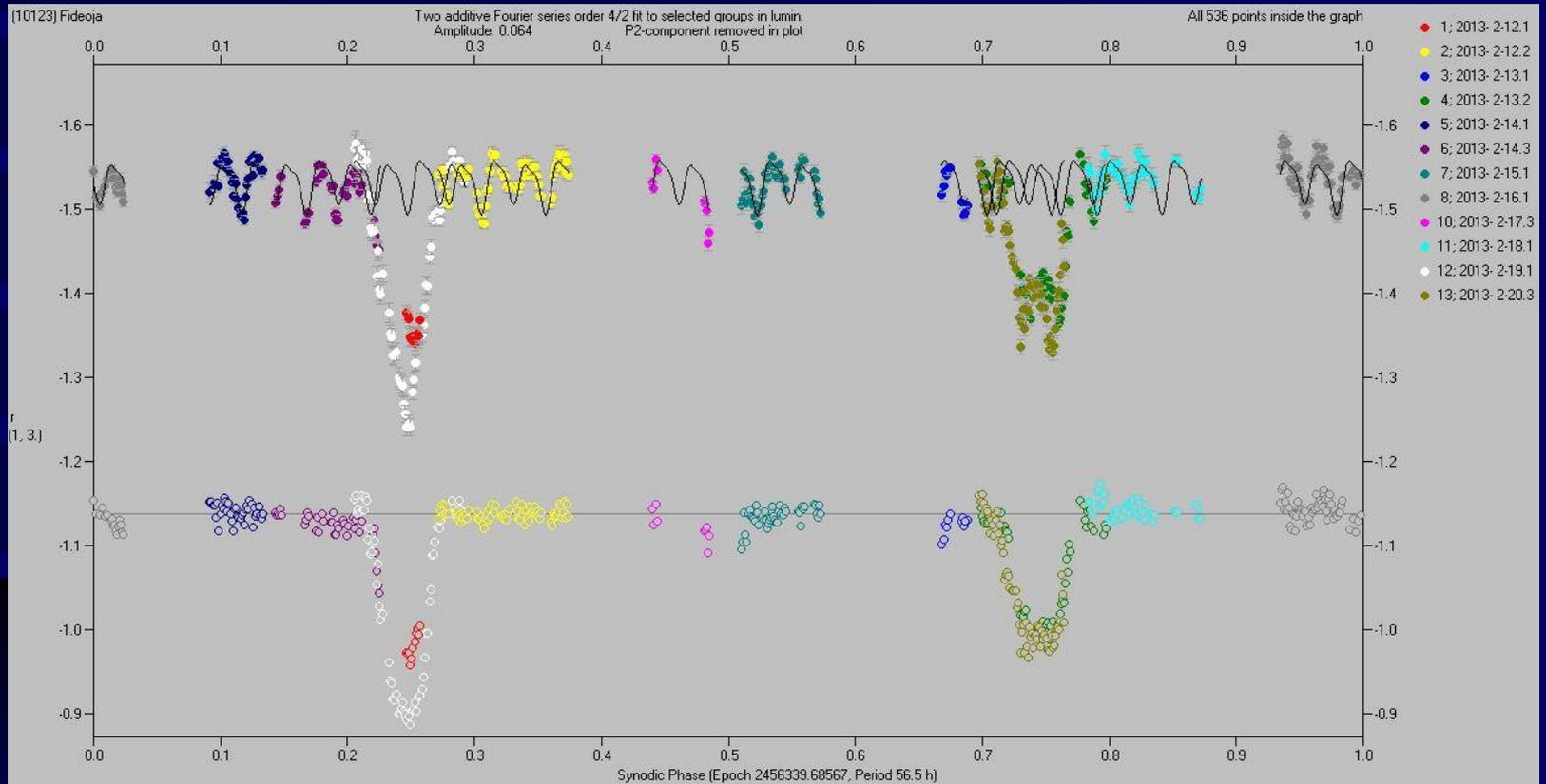
$P_{orb} = 56.5 \pm 0.1$ h
$P_1 = 2.8658 \pm 0.0003$ h
$D_2/D_1 = 0.39 \pm 0.02$

Photometric errors
0.011 mag

Paired binaries (6369) and (9783)
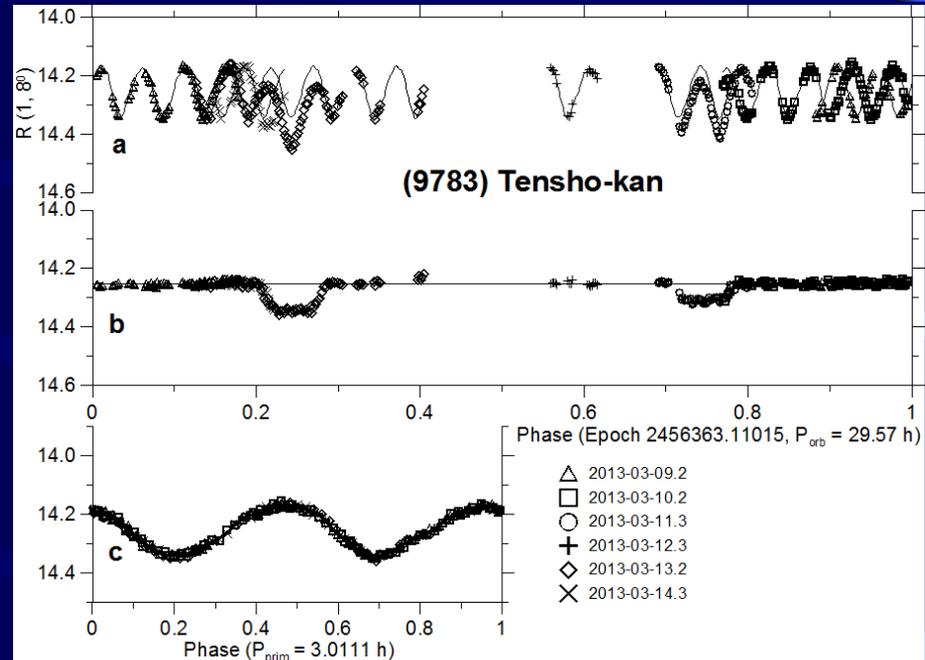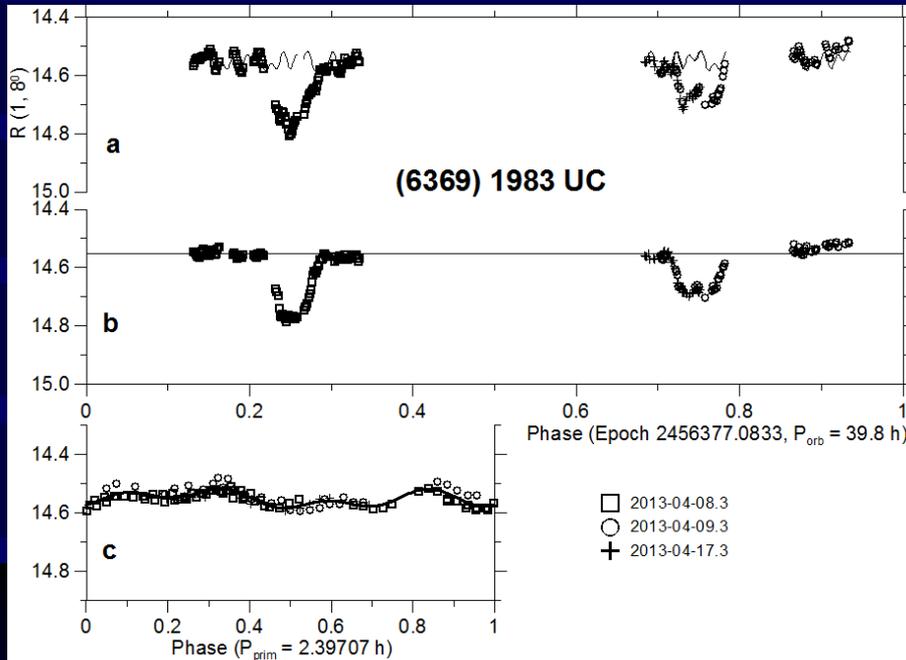
They look pretty much like classical (semi-)asynchronous binaries ---except for their relatively long orbital periods--- with near-critical total angular momentum and nearly-spheroidal primary.

But we'll look forward towards seeing more data from their return apparitions.

Photometric detection of binary system - principle

<u>Mutual occultation/eclipse events</u> between system components cause <u>brightness attenuations</u>.

Condition:
Earth or Sun close to the system's orbit plane.

Primary and secondary events (depending on which body is occulted/eclipsed).
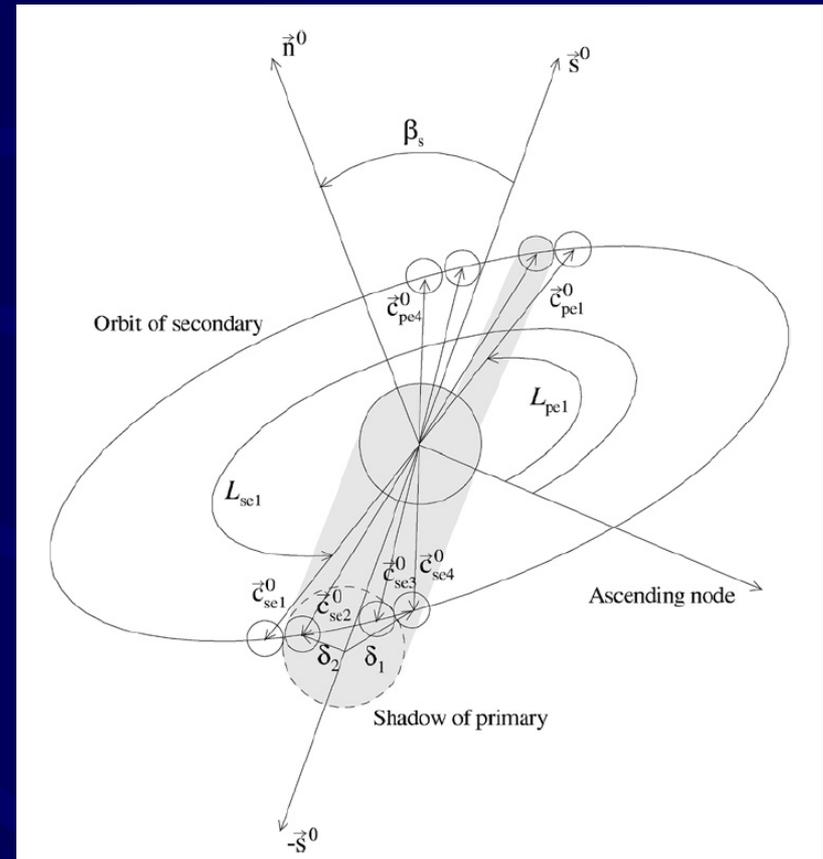
(Scheirich and Pravec 2009)

Asteroid pairs among small MBAs

Related to orbiting bound binaries – formation by rotational fission

(Tasks 2, 3 and 4)

Asteroid Itokawa

Can it fission when spun up?

図3 イトカワの +90 度面

Asteroid pairs
found on closely similar heliocentric orbits

Vokrouhlický and Nesvorný (Astron. J. 136, 280, 2008; VN08) found a population of pairs of asteroids residing on closely similar orbits.

Pravec and Vokrouhlický (Icarus 204, 580, 2009; PV09) extended the analysis and found numerous significant pairs up to $d = 36$ m/s (approx. the current relative encounter velocity between 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]

	a	e	i	Omega	omega
4765	1.9455258	0.0604289	23.70505	76.59085	108.05341
2001X0105	1.9455837	0.0604382	23.70634	76.52980	108.30700
	-0.0000578	-0.0000093	-0.00129	0.06105	-0.25359
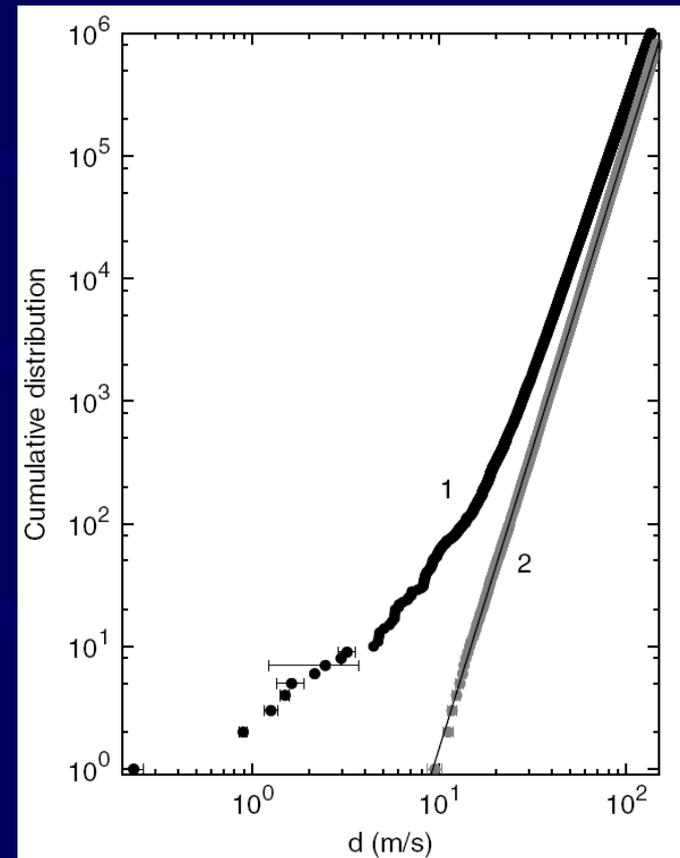
Pair formation by spin fission due to YORP spin-up

If mass ratio $\lesssim 0.2$

YORP
Spin-up
(~ 10s Myears)

Dynamic
Process
(< 1 year)

Rubble Pile Asteroid

Fissioned Proto-Binary

Escaping Secondary,
System becomes
Asteroid Pair
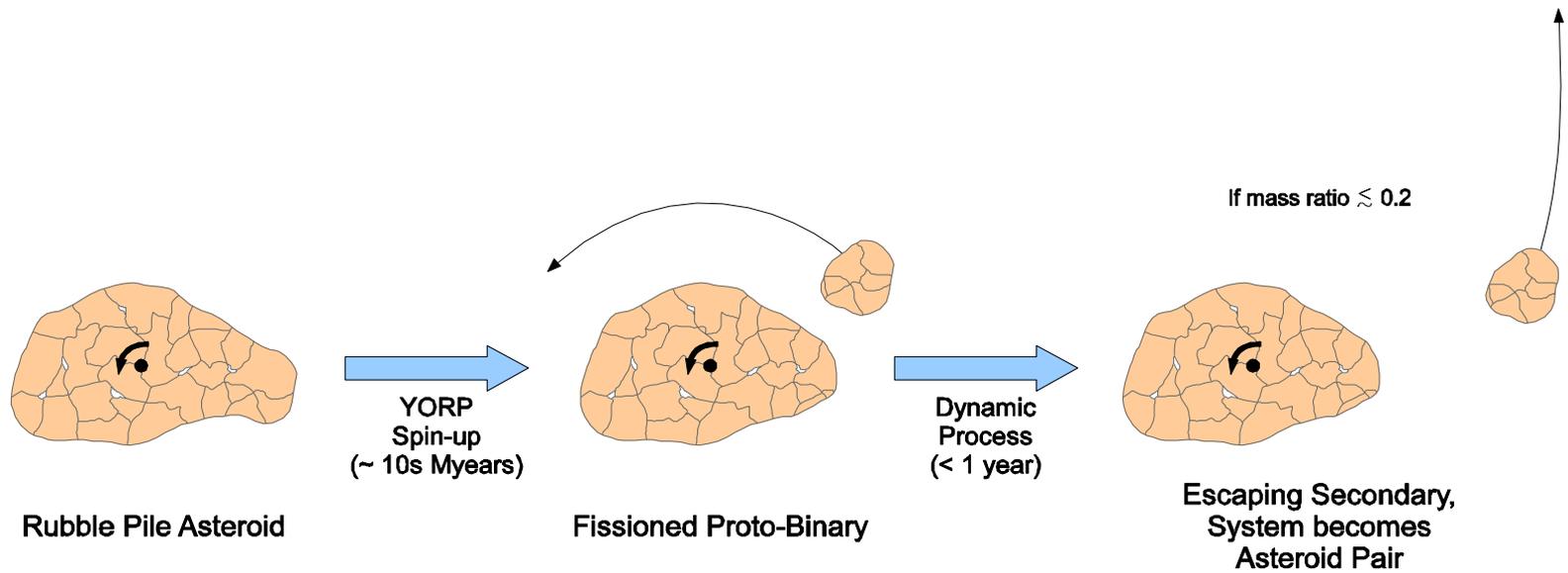
Rotational fission theory (Scheeres 2007, Pravec et al. 2010):

Spun-up by YORP, the "rubble pile" asteroid reaches a critical spin rate and fissions. The secondary orbiting the primary, energy being transferred from rotational to translational energy and vice-versa. If $q < \sim 0.2$, the proto-binary has a positive free energy and the two components can escape from each other, after a period of chaotic orbit evolution (~ several months), and become an "asteroid pair".

The total angular momentum and energy are, in general, conserved across fission but becomes decomposed into multiple components:

$$I \cdot \omega = I_1 \cdot \omega_1 + I_2 \cdot \omega_2 + \frac{M_1 M_2}{M_1 + M_2} r \times v \quad (7)$$

$$\frac{1}{2}\omega \cdot I \cdot \omega + \mathcal{U} = \frac{1}{2}\omega_1 \cdot I_1 \cdot \omega_1 + \frac{1}{2}\omega_2 \cdot I_2 \cdot \omega_2 + \frac{1}{2}\frac{M_1 M_2}{M_1 + M_2} v \cdot v + \mathcal{U}_{11} + \mathcal{U}_{22} + \mathcal{U}_{12} \quad (8)$$

where M_1 and M_2 are the masses of the two components, r and v are the relative position and velocity vector between these two components, $\mathcal{U}_{ii}$ is the self-potential of the new components and $\mathcal{U}_{12}$ is the mutual potential between the components.

$$\mathcal{U}_{12} = -G \int_{\beta_1} \int_{\beta_2} \frac{dm_1 dm_2}{|\rho_1 - \rho_2|} \quad (9)$$

The mutual potential represents a conduit for energy being transferred from rotational to translational energy and vice-versa and can be surprisingly effective.

Model of the proto-binary separation - explains the observed correlation P_1 vs q

Model curves for following parameters:

- α_L = 0.7, 1.0, 1.2
  (total angular momentum near the lower, middle and upper values observed in orbiting binary systems)

- initial separations A/b_1 = 2 and 4
  (orbit's semimajor axis/medium semiaxis of the primary)

- primary's equatorial axes ratio
  a_1/b_1 = 1.2 – 1.5 (from observed amplitudes).

Primaries of pairs with small mass ratios (q = 10^{-3} to a few 10^{-2}) rotate rapidly <u>near the critical fission frequency</u>.

As the mass ratio approaches the approximate cutoff limit of 0.2, the <u>primary period grows long</u>, as when the total energy of the system approaches zero to disrupt the asteroid pair must extract an increasing fraction of the primary's spin energy.

Asteroid pairs were formed by rotational fission of critically spinning parent asteroids. *(Pravec et al. 2010)*
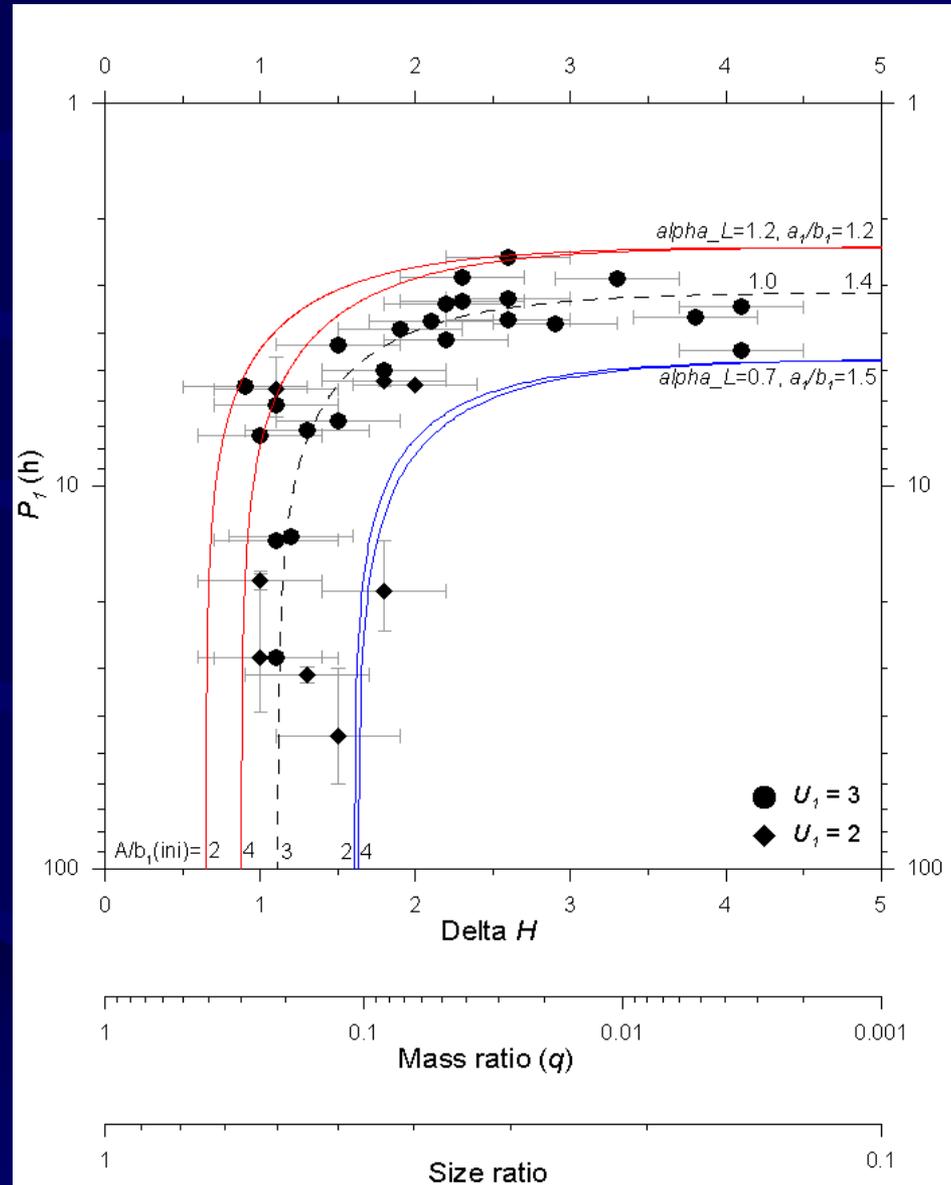
Yarkovsky-O'Keefe-Radzievskii-Paddack (YORP) effect

Changes asteroid spin vectors

- a key evolutionary process in small asteroids

(Task 5)

Yarkovsky-O'Keefe-Radzievskii-Paddack (YORP) effect

(Rubincam and Paddack 2007)

Yarkovsky-O'Keefe-Radzievskii-Paddack (YORP) effect

Fázový posun ve světelné křivce asteroidu (25143) Itokawa - projev YORPu
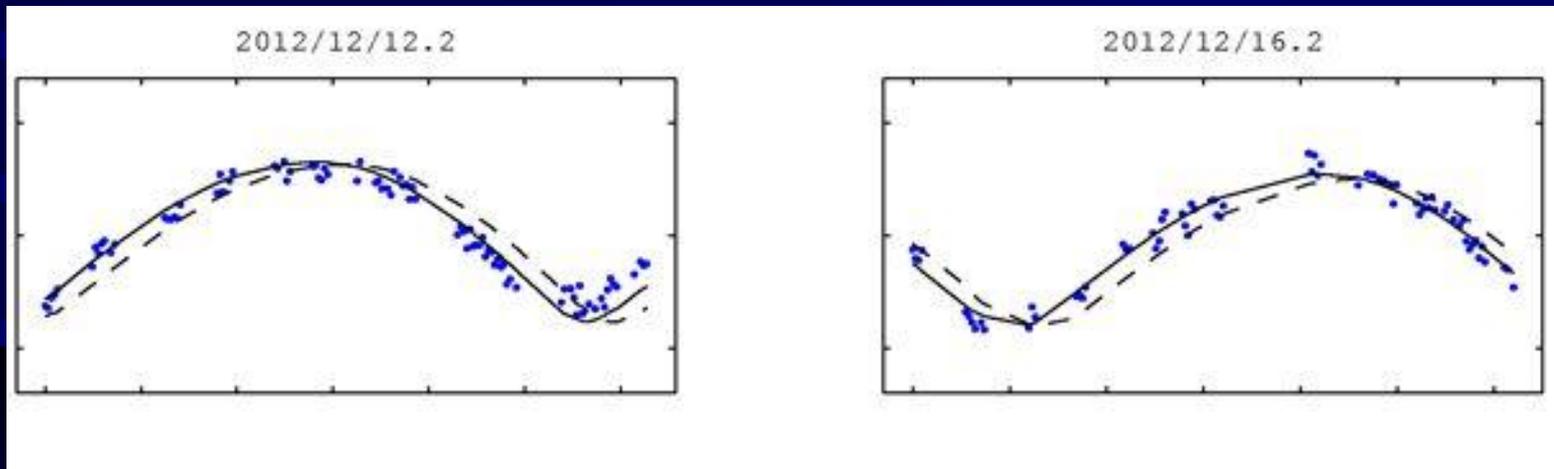
Non-principal axis rotators ("tumblers") among the smallest asteroids

Asteroids in excited rotation states

(Task 7)

Force-free precession

Non-principal axis rotation (free precession, tumbling) is a spin state with <u>higher than minimal rotational kinetic energy</u> for given angular momentum L.

The rotational motion can be described with the time evolution of the Euler angles *(e.g., Samarasinha and A'Hearn 1991, Kaasalainen 2001).*

It is a rotation around one of the extreme principal inertia axes and a precession of the axis around the L vector.

Two periods: P_φ, P_ψ

The rotational motion of an asteroid is described by

$$\vec{L} = \hat{I}\vec{\omega}, \qquad (1)$$

where $\vec{L}$ is the asteroid's angular momentum vector, $\hat{I}$ is its inertia tensor, and $\vec{\omega}$ is its angular velocity vector. The inertia tensor is generally a symmetric tensor containing six independent components. A convenient choice of the system of coordinates in the asteroid-fixed frame gives zero non-diagonal components. The diagonal components $I_1 \leqslant I_2 \leqslant I_3$ are then the principal moments of inertia; the axes are called the principal inertia axes.

The rotational kinetic energy is generally

$$E = \frac{1}{2}\vec{\omega}^T \hat{I}\vec{\omega} \qquad (2)$$

and particularly for the principal inertia axes choice of the system of coordinates

$$E = \frac{1}{2}(I_1\omega_1^2 + I_2\omega_2^2 + I_3\omega_3^2). \qquad (3)$$

(Pravec et al. 2005)

Appendix A: Force-free precession

Free precession has been well discussed by many authors (see, e.g., Samarasinha & A'Hearn 1991 and references therein). However, some subjects needed in the inverse problem require special attention, so I give a concise account of the dynamical problem here.

The time evolution of the Euler angles ϕ, θ, ψ is easy to derive from the basic kinematic equations (see, e.g., Goldstein 1980) that can be written as

$$\frac{L_1}{I_1} = \dot{\phi}\sin\theta\sin\psi + \dot{\theta}\cos\psi,$$
$$\frac{L_2}{I_2} = \dot{\phi}\sin\theta\cos\psi - \dot{\theta}\sin\psi, \qquad (A.1)$$
$$\frac{L_3}{I_3} = \dot{\phi}\cos\theta + \dot{\psi},$$

where L_i are the projections of the angular momentum vector $\mathbf{L}$ onto the principal axes of the tumbling inertia ellipsoid; $\mathbf{L}$ is constant in an inertial frame in torque-free precession. The components L_i are, by the definition of the Euler angles,

$$(L_1, L_2, L_3) = (L\sin\theta\sin\psi, L\sin\theta\cos\psi, L\cos\theta). \qquad (A.2)$$

Combining the two sets of equations, we get

$$\dot{\phi} = L(I_+ - I_-\cos 2\psi),$$
$$\dot{\theta} = LI_-\sin\theta\sin 2\psi, \qquad (A.3)$$
$$\dot{\psi} = \cos\theta\left(\frac{L}{I_3} - \dot{\phi}\right),$$

where $I_+ = \frac{1}{2}(I_1^{-1} + I_2^{-1})$ and $I_- = \frac{1}{2}(I_1^{-1} - I_2^{-1})$. The basic properties of the time evolution of the Euler angles are quite apparent from this set of equations: when

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pensive function calls to each point separately. It is useful to evaluate one quantity via an elliptic integral; this is the rotation period P_ψ, given by

$$P_\psi = 4\sqrt{\frac{I_1 I_2 I_3}{2E(I_1 - I_3)\left(I_2 - \frac{L^2}{2E}\right)}}\,K(k), \qquad (A.7)$$

where $K(k)$ is the complete elliptic integral $K(k) = \int_0^{\pi/2}(\sqrt{1 - k^2\sin^2 x})^{-1}\,dx$, and

$$k^2 = \frac{(I_2 - I_1)\left(\frac{L^2}{2E} - I_3\right)}{(I_1 - I_3)\left(I_2 - \frac{L^2}{2E}\right)}. \qquad (A.8)$$

(Kaasalainen 2001)

Using the constant

$$\Delta\phi = \int_0^{P_\psi}\dot{\phi}\,dt = 2\int_0^{P_\psi/2}\dot{\phi}\,dt \qquad (A.10)$$

(note that $\Delta\phi$ is independent of L, whose occurrences in P_ψ and $\dot{\phi}$ cancel each other out), we can define

$$P_\phi = 2\pi\frac{P_\psi}{\Delta\phi}. \qquad (A.11)$$

Tumbler lightcurve

Lightcurve of a tumbling asteroid can be expanded with the Fourier series in the two angular variables *(Kaasalainen 2001, Pravec et al. 2005).*

In a tumbler's lightcurve, we observe the frequencies $f_\varphi = P_\varphi^{-1}$, $f_\psi = P_\psi^{-1}$, and their linear combinations.

The highest signal is often observed in the second harmonic of $(f_\varphi \pm f_\psi)$; it is the actual mean frequency of rotation of the body around the instantaneous spin axis.

Appendix A. Fourier series in two dimensions

A function $F(\psi, \phi)$, where ψ, ϕ are angular variables over $\langle -\pi, \pi \rangle$, can be expanded with Fourier series in the two variables (Rektorys et al., 1988):

$$F(\psi, \phi) = \sum_{j,k=0}^{\infty} [a_{jk} \cos j\psi \cos k\phi + b_{jk} \sin j\psi \cos k\phi + c_{jk} \cos j\psi \sin k\phi + d_{jk} \sin j\psi \sin k\phi], \quad (A.1)$$

where

$$a_{jk} = \frac{\lambda_{jk}}{\pi^2} \int_{-\pi}^{\pi} \int_{-\pi}^{\pi} F(\psi, \phi) \cos j\psi \cos k\phi \, d\psi \, d\phi, \quad (A.2)$$

$$b_{jk} = \frac{\lambda_{jk}}{\pi^2} \int_{-\pi}^{\pi} \int_{-\pi}^{\pi} F(\psi, \phi) \sin j\psi \cos k\phi \, d\psi \, d\phi, \quad (A.3)$$

$$c_{jk} = \frac{\lambda_{jk}}{\pi^2} \int_{-\pi}^{\pi} \int_{-\pi}^{\pi} F(\psi, \phi) \cos j\psi \sin k\phi \, d\psi \, d\phi, \quad (A.4)$$

$$d_{jk} = \frac{\lambda_{jk}}{\pi^2} \int_{-\pi}^{\pi} \int_{-\pi}^{\pi} F(\psi, \phi) \sin j\psi \sin k\phi \, d\psi \, d\phi, \quad (A.5)$$

$$\lambda_{jk} = \left(\frac{1}{2}\right)^{\delta_j^0} \left(\frac{1}{2}\right)^{\delta_k^0}, \quad (A.6)$$

and δ_i^0 is Kronecker's delta.

The Fourier series given by Eq. (A.1) can be rewritten into a following form that is convenient for some purposes:

$$F(\psi, \phi) = C_0 + \sum_{j=1}^{\infty} [C_{j0} \cos j\psi + S_{j0} \sin j\psi]$$

$$+ \sum_{k=1}^{\infty} \sum_{j=-\infty}^{\infty} \big[C_{jk} \cos(j\psi + k\phi) + S_{jk} \sin(j\psi + k\phi) \big], \quad (A.7)$$

where

$$C_0 = a_{00}, \quad C_{j0} = a_{j0}, \quad S_{j0} = b_{j0},$$

$$C_{0k} = a_{0k}, \quad S_{0k} = c_{0k},$$

$$C_{\pm j,k} = \frac{a_{jk} \pm d_{jk}}{2}, \quad S_{\pm j,k} = \frac{c_{jk} \pm b_{jk}}{2},$$

$$\text{for } j, k > 0. \quad (A.8)$$

(Pravec et al. 2005)

# Lightcurve of a fast spinning tumbler (2002 TD60)
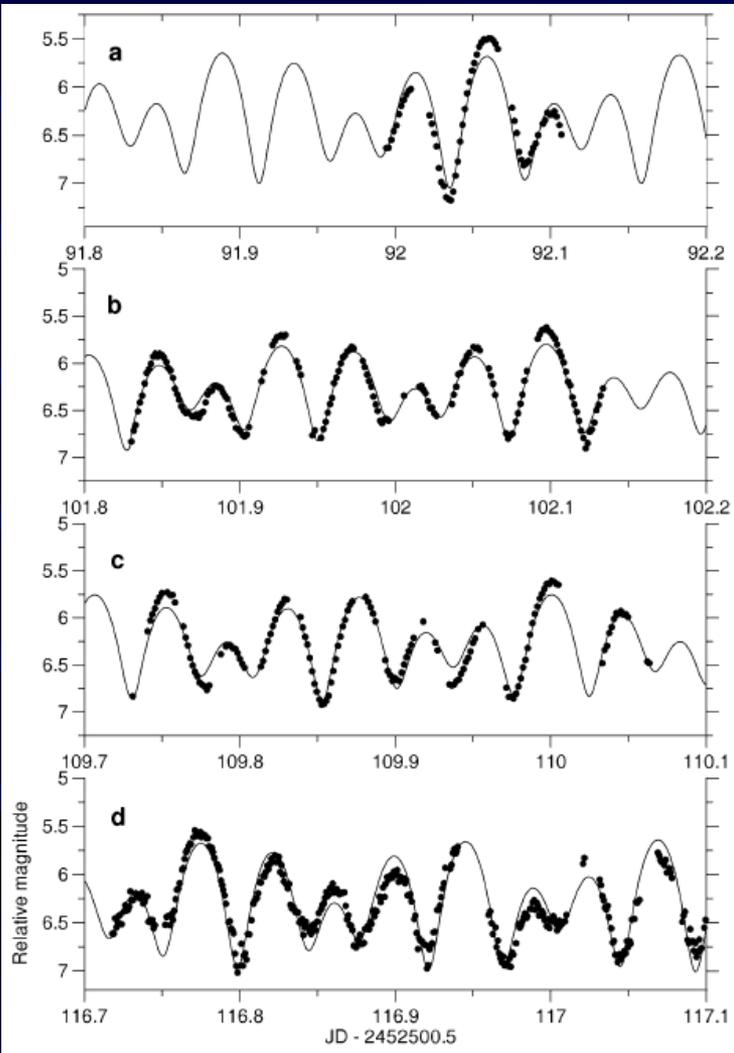
Fig. 4. Lightcurve data of 2002 TD60 of (a) 2002-11-14.1, (b) 11-24.0, (c) 12-01.9, and (d) 12-08.9, respectively. Curve is the best-fit synthetic lightcurve of the prograde solution of the numerical model. The other, mirror solution (retrograde) gives a curve indistinguishable from the plotted one.
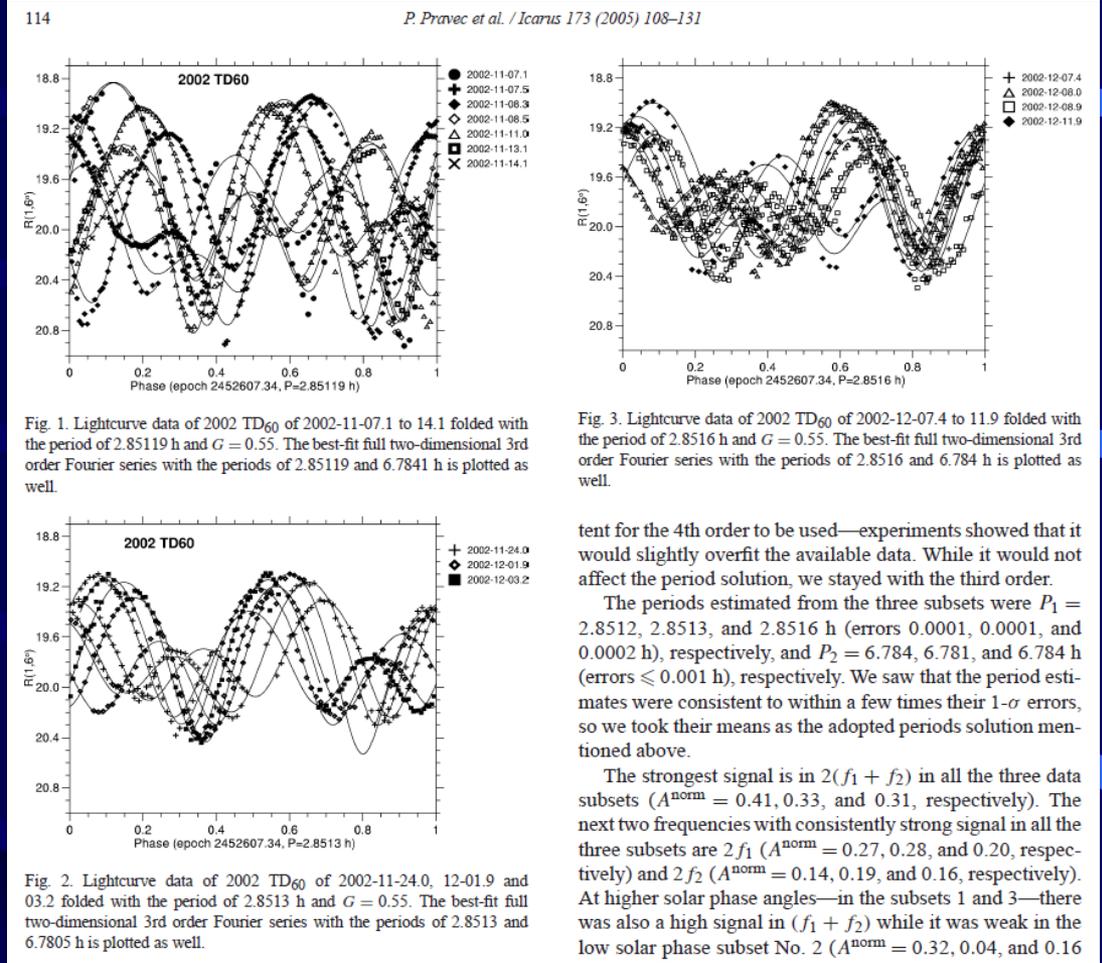
Fig. 1. Lightcurve data of 2002 TD60 of 2002-11-07.1 to 14.1 folded with the period of 2.85119 h and $G = 0.55$. The best-fit full two-dimensional 3rd order Fourier series with the periods of 2.85119 and 6.7841 h is plotted as well.

Fig. 3. Lightcurve data of 2002 TD60 of 2002-12-07.4 to 11.9 folded with the period of 2.8516 h and $G = 0.55$. The best-fit full two-dimensional 3rd order Fourier series with the periods of 2.8516 and 6.784 h is plotted as well.

Fig. 2. Lightcurve data of 2002 TD60 of 2002-11-24.0, 12-01.9 and 03.2 folded with the period of 2.8513 h and $G = 0.55$. The best-fit full two-dimensional 3rd order Fourier series with the periods of 2.8513 and 6.7805 h is plotted as well.

tent for the 4th order to be used—experiments showed that it would slightly overfit the available data. While it would not affect the period solution, we stayed with the third order.

The periods estimated from the three subsets were $P_1 = 2.8512, 2.8513$, and 2.8516 h (errors 0.0001, 0.0001, and 0.0002 h), respectively, and $P_2 = 6.784, 6.781$, and 6.784 h (errors $\leqslant 0.001$ h), respectively. We saw that the period estimates were consistent to within a few times their 1-σ errors, so we took their means as the adopted periods solution mentioned above.

The strongest signal is in $2(f_1 + f_2)$ in all the three data subsets ($A^{norm} = 0.41, 0.33$, and 0.31, respectively). The next two frequencies with consistently strong signal in all the three subsets are $2f_1$ ($A^{norm} = 0.27, 0.28$, and 0.20, respectively) and $2f_2$ ($A^{norm} = 0.14, 0.19$, and 0.16, respectively). At higher solar phase angles—in the subsets 1 and 3—there was also a high signal in $(f_1 + f_2)$ while it was weak in the low solar phase subset No. 2 ($A^{norm} = 0.32, 0.04$, and 0.16

(Pravec et al. 2005)

2008 TC3 numerical model

- Best-fit shape:

(Scheirich et al. 2010)
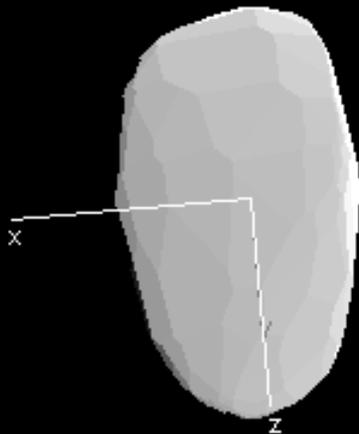
Dimensions ratio:

z/x = 2.4
y/x = 1.3

The shape is convex model only!

(99942) Apophis

A 400-meter asteroid with a small but non-zero Earth impact probability (several possible impact dates in the 21st century; Farnocchia et al., 2013).

The most significant uncertainty in the prediction - an unknown magnitude and sign of the Yarkovsky drift of the Apophis' orbit.

The Yarkovsky drift depends on asteroid's spin state, angular momentum vector, and size.

Little was known about its spin before; limited data by Behrend et al. suggested a slow rotation with a period about 30 hours.

Our analysis of their data indicated a possibility that it might be tumbling.

We undertook the task of establishing its spin state within our NEOSource project.

Photometry of Apophis

<u>Apparition</u>: 2012 Dec. 23 – 2013 April 15

<u>Data</u> from
35 nights with the 1.54-m Danish telescope, La Silla
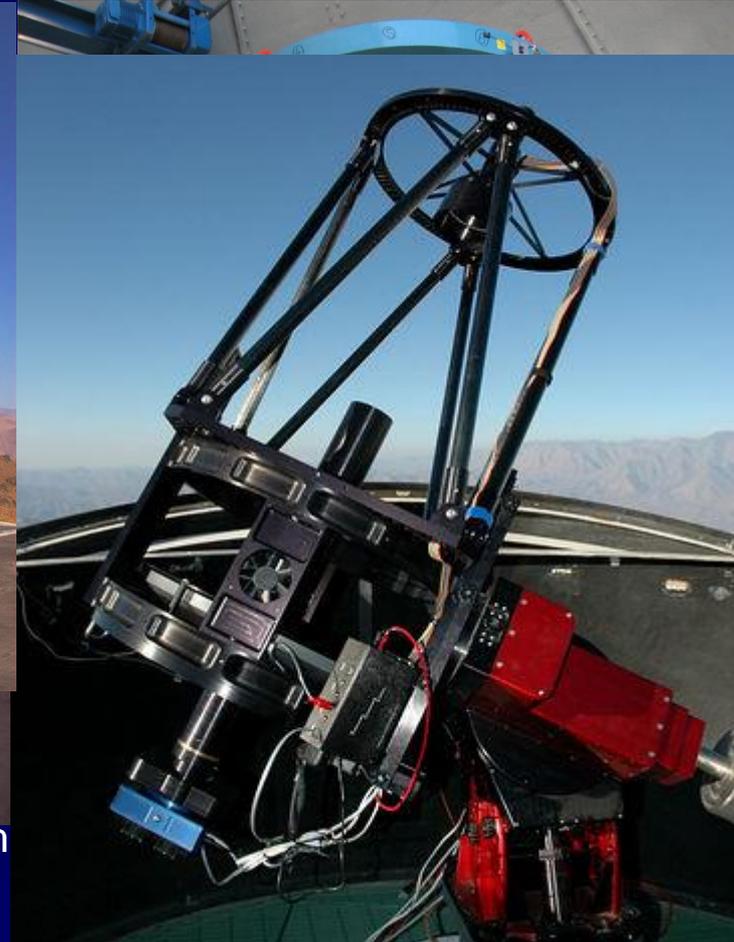
topography especially in lightcurve minima –> am

Apophis' tumbling

(99942) Apophis
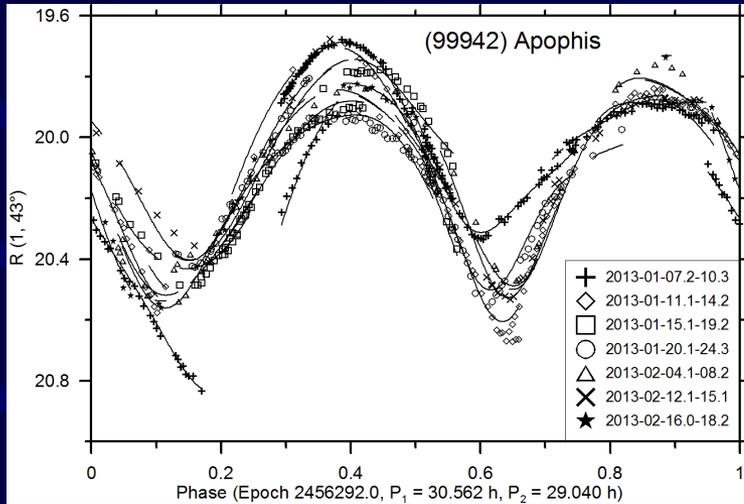
Table 2
Parameters of the Apophis model with their estimated admissible uncertainties (corresponding to 3σ confidence level).

Fitted parameters	
λ_L (°)	250[a]
β_L (°)	−75
ϕ_0 (°)	152^{+173}_{-64}
ψ_0 (°)	14^{+44}_{-11}
P_ψ (h)	263 ± 6
P_ϕ (h)	27.38 ± 0.07
$I_a \equiv I_1/I_3$	$0.61^{+0.11}_{-0.08}$
$I_b \equiv I_2/I_3$	$0.965^{+0.009}_{-0.015}$
Derived parameters	
$\left(P_\phi^{-1} - P_\psi^{-1}\right)^{-1} = P_1$ (h)	30.56 ± 0.01
θ_{min} (°)	12 ± 4
θ_{max} (°)	55^{+9}_{-20}
θ_{aver} (°)	37^{+6}_{-14}
a_{dyn}/c_{dyn}	1.51 ± 0.18
b_{dyn}/c_{dyn}	1.06 ± 0.02
a_{shp}/c_{shp}	1.64 ± 0.09
b_{shp}/c_{shp}	$1.14^{+0.04}_{-0.08}$
E/E_0	1.024 ± 0.013

The angles ϕ_0 and ψ_0 are for the epoch JD 2456284.676388 (=2012 December 23.176388 UT), light-travel time corrected (i.e., asterocentric).
E/E_0 is a ratio of the rotational kinetic energy and the lowest energy for given angular momentum, defined as $E_0 = L^2/(2I_3)$.
[a] The major and minor semiaxes of the uncertainty area of the direction of $\vec{L}$ are 27° and 14°, respectively, see Fig. 4.
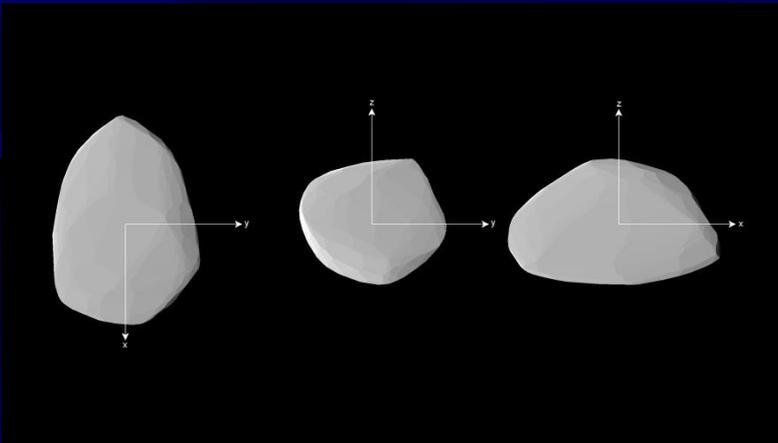
For the Apophis' spin state, the impact on 2068 April 12 is possible. Its probability is still low, on an order of 10^{-5}, but it requires more study, observations and modeling.

Conclusions

The Danish 1.54-m telescope is a small but very good dedicated photometric telescope.

It is a great instrument for observations requiring long time series.

Taking them is possible for the combination of the capabilities of the telescope system allowing inexpensive remote observations, the exceptional quality of the sky on La Silla, and the collaborative spirit of the people running the telescope (the Danish team, the Czech team, and the ESO La Silla staff).

We are getting unique data and results on properties and processes in near-Earth asteroids in particular.