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Datura family: the 2009 update★

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ABSTRACT

Context. Research of asteroid families has been recently refreshed by the discovery of very young ones. These families are of great interest because they represent the product of their parent body fragmentation before orbital and physical evolutionary processes can change them. A cluster of seven objects around the largest body (1270) Datura is of particular interest because it has enough known members and resides in the inner part of the main asteroid belt, facilitating observations.

Aims. We carried out photometric observations of the two largest members of the Datura family – asteroids (1270) Datura and (90265) 2003 CL5 – with the goal of inferring their physical parameters. We also used numerous astrometric observations of Datura-family members in the past few years to revisit the age of this cluster.

Methods. We performed numerous photometric observations of (1270) Datura over several oppositions. We then used the lightcurve inversion method to determine the spin state and shape of this asteroid. In the case of (90265) 2003 CL5, for which only limited lightcurve data have been acquired so far, we used Fourier analysis to determine the synodic rotation period during the 2008 apparition. We also used backward numerical integration of the improved orbits of Datura family members to reduce uncertainty in its age.

Results. We determined the rotation state of (1270) Datura, the largest member of its own family. Its major properties are a short rotation period of ∼3.36 h and small obliquity, which, however, exhibits ∼±15° excursions because of a forced Cassini state of the proper nodal frequency. Any possible initial non-principal rotation state has probably been damped and the asteroid rotates about the shortest axis of the inertia tensor. Its global shape, although convex in our representation, may reflect regions related to the excavation of the family members from the parent body surface. Interestingly, the second largest member of the Datura family – (90265) 2003 CL5 – appears to be very slow rotator with the rotation period ∼24 h. The large amplitude of its rotation curve suggests that its shape is extremely elongated, possibly bi-lobed. Improved orbits of the family members allow us to re-determine the possible age of this family. We find an age that is slightly older than previously reported. Using a conservative approach, we obtain an age in the 450 to 600 kyr range. With strengthened, but plausible, conditions, we find that the current data may support an age of 530 ± 20 kyr. Further astrometric and photometric observations of the Datura cluster members are needed to determine its age more accurately.

Key words. minor planets, asteroids – techniques: photometric

1. Introduction

The discovery of very young asteroid clusters (e.g., Nesvorný et al. 2006b; Nesvorný & Vokrouhlický 2006; Pravec & Vokrouhlický 2009) started a new phase in the analysis of the asteroid families. This is because we have become aware of many dynamical and physical processes that modify the configuration and the observable parameters of their individual members with time. These processes prevent information about the initial state of the asteroid families being derived from current observations. In very young families, of ages less than one million years, most of these processes had insufficient time to affect the physical properties of both their members and their overall orbital configuration. From their study, we might be able to directly infer properties of their parent object fragmentation. The very young asteroid families may also have some novel features in terms of the interplanetary dust distribution (e.g., Vokrouhlický et al. 2008; Espy et al. 2009).

Spectroscopic studies with the goal of calibrating space weathering processes and spectral uniformity as a function of the rotational cycle are ongoing (Mothé-Diniz & Nesvorný 2008; Takato 2008; Chapman et al. 2009; Vernazza et al. 2009). Here we begin attempts to characterize the rotational state of the young families' members. We focus on the Datura family for two reasons: (i) this cluster has a wealth of currently known members (Table 1); and (ii) residing in the inner part of the asteroid belt, its largest members are assessable for physical studies to

★ Photometric data is only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/507/495

Table 1. Equinoctial orbital elements of the Datura family members as of MJD 55000.0.

Asteroid		a (AU)	h	k	p	q	λ (deg)	H (mag)
1270	Datura	2.234174257	–0.011875952	0.207687578	0.051822853	–0.007173173	255.1130024	12.5
60151	1999 UZ6	2.234822624	–0.009607219	0.207400245	0.051977826	–0.006192689	359.3410694	16.3
89309	2001 VN36	2.235539500	–0.000580046	0.206418404	0.052524410	–0.002728416	144.4047913	16.3
90265	2003 CL5	2.235067633	–0.008823212	0.207320052	0.052108104	–0.005199203	74.6438215	15.4
203370	2001 WY35	2.235204060	–0.009678118	0.207279389	0.051955550	–0.006259748	138.6271217	17.2
215619	2003 SQ168	2.234139912	–0.011368414	0.207703517	0.051883691	–0.006800068	256.8712362	17.0
	2003 UD112	2.232935554	–0.004638856	0.206700860	0.052182950	–0.004986937	266.2149719	17.9
Uncertainty		δa	δh	δk	δp	δq	$\delta\lambda$	
1270	Datura	1.1e-8	7.3e-8	9.2e-8	7.0e-8	8.8e-8	8.4e-6	
60151	1999 UZ6	8.5e-8	2.4e-7	2.0e-7	1.5e-7	1.6e-7	3.4e-5	
89309	2001 VN36	7.7e-8	2.7e-7	2.3e-7	1.5e-7	1.4e-7	2.8e-5	
90265	2003 CL5	4.9e-8	1.8e-7	1.6e-7	1.4e-7	1.5e-7	2.0e-5	
203370	2001 WY35	1.1e-7	4.6e-7	2.9e-7	2.3e-7	1.8e-7	5.1e-5	
215619	2003 SQ168	2.2e-7	4.3e-7	4.1e-7	1.9e-7	3.7e-7	6.3e-5	
	2003 UD112	1.8e-3	8.8e-4	5.2e-4	7.7e-5	5.6e-5	7.4e-1	

a is semimajor axis, $(h,k) = e\,(\sin\varpi, \cos\varpi)$ where e is the eccentricity and ϖ is the longitude of perihelion, $(p,q) = \tan(i/2)\,(\sin\Omega, \cos\Omega)$ where i is the inclination and Ω is the longitude of node, and $\lambda = \varpi + M$ is the mean longitude in orbit (M is the mean anomaly). Default reference system is that of mean ecliptic J2000. Orbital solution, together with formal standard deviation uncertainties, is from the AstDyS catalog as of May 2009 (e.g., Knežević et al. 2002). The adopted absolute magnitude values H are from MPC; in general, their uncertainty is ±0.5 mag. Note the last member, 2003 UD112, is a single-opposition asteroid with a very loosely determined orbit.

even limited-size instrumentation. Our ideal goal would be to determine the spin state and shape of as many members as possible, and relate them to their initial values immediately after the family formation. We shall see, however, that already in the (1270) Datura case (Sect. 3) the analysis may not be straightforward, and sometimes we may only be able to infer lower and upper bounds to the initial spin state. So far we have succeeded in acquiring photometric observations of (1270) Datura and the second largest member in its family (90265) 2003 CL5. While in the first case, we have already sufficient data to reconstruct the current spin state and shape (Sect. 3), in the case of asteroid 2003 CL5, we present only single-opposition data that poorly provides a constraint on its rotation period. Nevertheless, we find that this incomplete information is very interesting because of the large disparity in the rotation rate of the two largest members in this family and the likely bi-lobed shape of 2003 CL5 (Sect. 4). In the second part of the paper, we revise the age of this family using new astrometric observations of the Datura family members acquired since January 2006, and especially recovery of the asteroid (215619) 2003 SQ168 in December 2007 (Sect. 5). With six members on reasonably well-constrained orbits (Table 1), we are able to reconstruct the past configuration of this asteroid cluster to higher accuracy than before. Surprisingly, we find possible age solutions that are older than the value of ~450 kyr previously reported by Nesvorný et al. (2006b).

2. Observations

With its near 10 km size, Datura is a relatively easy target for photometric studies. It was observed by Wisniewski et al. (1997) during the 1990/1991 opposition, and Székely et al. (2005) during the 2000 opposition. Analyses of both datasets indicated relatively short rotation period of ~3.2−3.4 h, but they were limited enough to allow linkage across the 10 yr interval of time between them.

The discovery of the Datura family in late 2005 provided strong motivation for photometric and spectroscopic observations to infer the physical properties of (1270) Datura and other members of its family. We started our photometric campaign during the 2006 opposition and continued during subsequent observing time opportunities. Our main efforts were concentrated on the 2007/2008 opposition when observations covering a period of nearly six months, and phase angle values of up to 26°, were obtained (we did not use the independent observations of Takato (2008) from mid February 2008 because they roughly coincided with our data from the beginning of February 2008). These observations were very important because they allowed easy linkage of data from all oppositions and helped us to resolve the asteroid shape. The synodic period determined by combining lightcurves from this opposition, 3.3583 h, also served as a good starting value of the sidereal rotation period in the global lightcurve inversion procedure. We note however, that the data in 2006 and 2009 are also important, because they offer novel viewing geometry to the asteroid, thus helping us to resolve its pole and shape. The calibrated observations of November 20/21, 2007 allowed us to determine the color indexes $B - V = 0.81 \pm 0.07$, $V - R = 0.44 \pm 0.03$, and $R - I = 0.36 \pm 0.05$, which are typical of S type asteroids (e.g., Shevchenko & Lupishko 1998). Additional calibrated observations at different phase angles in R band allowed us to fit $H_0(R) = 12.03 \pm 0.02$, at maximum lightcurve, and $G(R) = 0.29 \pm 0.01$ using the $H - G$ system (see Fig. A.4 in the Appendix). Using our derived $V - R$ value, we then obtained $H_0 = 12.47 \pm 0.05$ in visible band, which infers an equivalent diameter of ~9.8 km (for an albedo of 0.19). Details of observing geometries for all 20 new lightcurves, including the 3 old ones, are given in Table 2.

The ~3 km size asteroid (90265) 2003 CL5, the second largest in the Datura family, is a significantly more difficult target for small-scale telescopes. Fortunately, the asteroid was close to the pericenter of its heliocentric orbit during opposition in 2008 enabling our observations to take place. We performed lightcurve observations of (90265) 2003 CL5 in five nights during this favorable apparition with the date and observing geometries indicated in Table 3. All observations were performed with the 1 m telescope at the Crimean Astrophysical Observatory at Simeiz. Three observations of (90265) 2003 CL5 were calibrated and performed in the standard R band. We also obtained a color index $V - R = 0.43 \pm 0.02$ that fits well the Datura value

Table 2. Aspect data for observations of (1270) Datura.

Date	r [AU]	Δ [AU]	α [deg]	λ [deg]	β [deg]	Obs.
1990 11 18.5	2.058	1.177	16.5	92.1	−4.0	W97
1991 01 16.2	2.201	1.334	15.6	78.6	−0.7	W97
2000 10 14.0	1.955	1.341	28.1	88.2	−5.4	S05
2006 07 08.0	2.078	1.096	10.0	264.8	0.6	PdM
2006 07 27.8	2.031	1.166	19.9	261.6	−0.7	SAAO
2006 07 29.8	2.026	1.176	20.7	261.5	−0.8	SAAO
2007 10 20.0	2.245	2.185	25.9	125.8	0.2	S
2007 10 21.0	2.247	2.176	26.0	126.1	0.2	S
2007 10 21.1	2.247	2.174	26.0	126.1	0.2	PdM
2007 11 17.2	2.310	1.894	24.8	132.4	1.2	PdM
2007 11 21.0	2.319	1.854	24.3	132.9	1.4	S
2007 11 28.1	2.335	1.782	23.1	133.7	1.7	PdM
2007 12 01.1	2.342	1.753	22.5	133.9	1.9	PdM
2008 01 06.0	2.418	1.495	10.2	130.6	3.7	K
2008 01 15.8	2.437	1.471	5.5	128.1	4.2	S
2008 02 02.9	2.472	1.498	4.5	123.0	4.8	PdM
2008 02 03.9	2.474	1.502	4.9	122.8	4.9	S
2008 04 09.8	2.581	2.221	22.5	119.6	4.9	K
2009 02 27.0	2.599	2.104	21.1	229.4	6.9	S
2009 03 04.1	2.593	2.034	20.5	229.9	7.1	S
2009 05 04.0	2.499	1.497	3.3	222.4	8.2	B
2009 05 14.0	2.481	1.493	6.3	219.7	7.9	B
2009 06 12.9	2.423	1.623	18.2	214.3	6.4	PdM

The first three are archival while the next 20 are new. The table lists Datura's distance from the Sun r and from the Earth Δ, the solar phase angle α, the geocentric ecliptic coordinates of the asteroid (λ,β), and the observatory (W97 – Wisniewski et al. 1997; S05 – Székely et al. 2005; PdM – Pic du Midi, 1 m; SAAO – South African Astronomical Observatory, 1 m; K – Kharkiv Observatory, 70 cm; S – Simeiz Observatory, 1 m; B – Borowiec Observatory, 0.5 m).

Table 3. Aspect data for new observations of (90265) 2003 CL5.

Date	r [AU]	Δ [AU]	α [deg]	λ [deg]	β [deg]	Obs.
2008 09 02.0	1.779	0.789	9.6	351.3	−12.7	S
2008 09 02.9	1.778	0.788	9.2	351.1	−12.8	S
2008 09 30.8	1.771	0.815	14.2	345.6	−13.0	S
2008 10 28.8	1.779	0.979	25.7	345.4	−10.9	S
2008 10 29.8	1.780	0.986	26.0	345.5	−10.8	S

The table lists target's distance from the Sun r and from the Earth Δ, the solar phase angle α, the geocentric ecliptic coordinates of the asteroid (λ,β), and the observatory. All observations were taken using the 1 m telescope at Simeiz Astrophysical Observatory, Crimea.

given above and the spectral classification S for this object (e.g., Mothé-Diniz & Nesvorný 2008).

Assuming a phase/slope parameter $G = 0.2$, our calibrated observations allow us to determine absolute magnitude $H_0 = 15.79 \pm 0.05$ in visible band at the maximum of the lightcurve (in this case, the phase-angle analysis was partly affected by the slow rotation of the asteroid and thus different observations were obtained at different phases of the rotation curve). Assuming an albedo of 0.19, this translates into a 2.1 km size equivalent to the maximal projection of the system. This is a slightly smaller value than reported so far from photometry accompanying the astrometric observations.

3. Spin state and shape of (1270) Datura

Our new observations were combined with the older data of Wisniewski et al. (1997) and Székely et al. (2005), and analysed using the lightcurve inversion method of Kaasalainen and collaborators (e.g., Kaasalainen et al. 2001, 2003). This procedure provides a simultaneous solution of the fundamental rotation parameters, rotation period P, and pole position (λ,β), in addition to parameters describing the irregular shape of the asteroid. Low-to-moderate phase angle lightcurves are insensitive to concavities in the asteroid shape, so we are generally only able to solve for a convex realization of the body (e.g., Ďurech & Kaasalainen 2003). Thus, we are unable to directly study the potential concavities of the shape that might indicate details of the fragmentation of the parent body of the family. Nevertheless, the flat planar areas in the derived figure are indicative of the presence of these concavities. The lightcurve inversion procedure also did not require a non-principal axis (NPA) component indicating that Datura rotates close enough to the shortest axis of its inertia tensor. Moderate initial NPA rotation would in all cases be damped with a characteristic timescale of ∼75 kyr if we adopted the parameters in Harris (1994), short enough compared to the estimated family age. So the present principal axis rotation does not preclude initial NPA[1].

As usual for main-belt targets, the lightcurve inversion method is affected by a ∼180° ambiguity in the pole longitude. We thus obtained two possible pole positions: (i) $\lambda = 60°$, $\beta = 76°$ (hereafter P1); and (ii) $\lambda = 264°$, $\beta = 77°$ (hereafter P2) with sidereal rotation period $P = 3.358100 \pm 0.000003$ h. In each of the cases, the uncertainty in the pole direction is roughly 5°. We note that P1 provides a slightly better fit to the lightcurves, but P2 cannot be ruled out on the base of the photometric data. Interestingly, well-planned infrared observations could not only improve the size/albedo values for Datura but also help to discriminate between P1 and P2 (see, e.g., Delbó & Tanga 2009).

Our solution supersedes an attempt of Ďurech et al. (2009), who used the 1990/1991 lightcurves of Wisniewski et al. (1997) and complemented them with 79 sparse photometry data from the US Naval Observatory catalog. The latitude solution in this reference differs significantly from our result, probably because of the limited quality of the dense-photometry data and the small amount of sparse-photometry data. This example illustrates the continuing necessity to acquire dense photometry data, to supplement possibly for more numerous amount of sparse data from the sky-survey programs in the future.

The convex shape model of (1270) Datura associated with the P1 solution is shown in Fig. 1 and six representative lightcurves and the corresponding fits are shown in Fig. 2. The planar regions in the northern and southern hemispheres are probably not real, but caused by the apriori convex representation of the model. It is interesting to hypothesize that one, or both, may correspond to the impact feature related to the origin of the Datura family.

3.1. What was the initial obliquity of Datura?

Given the youth of the Datura family, one is tempted to interpret the current rotation state as the initial one, right after the family formation event. We assume that this is true for the short rotation period, because the only sizeable phenomenon, the

[1] The derived shape model together with the complete lightcurve data set is available at astro.troja.mff.cuni.cz/projects/asteroids3D.

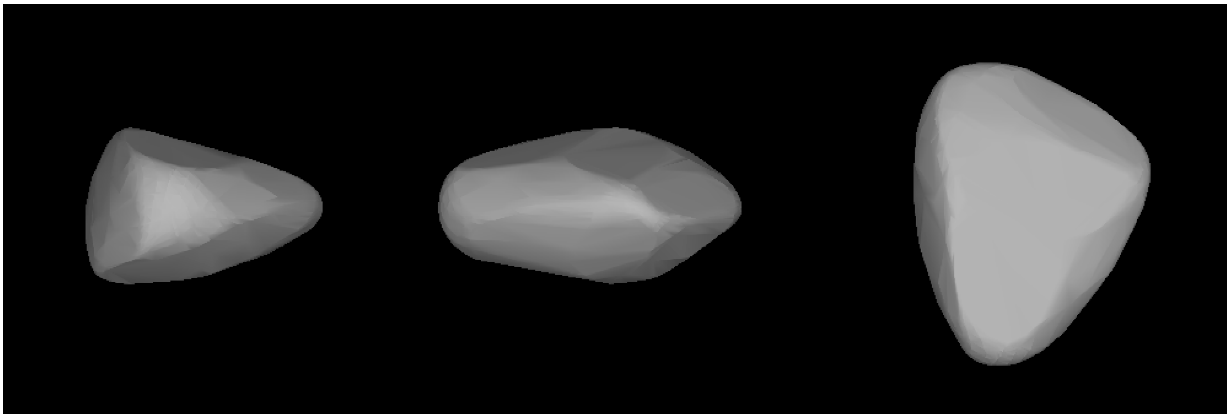

Fig. 1. The shape model of (1270) Datura shown from equatorial level (*left and center*, 90° apart) and pole-on (*right*).

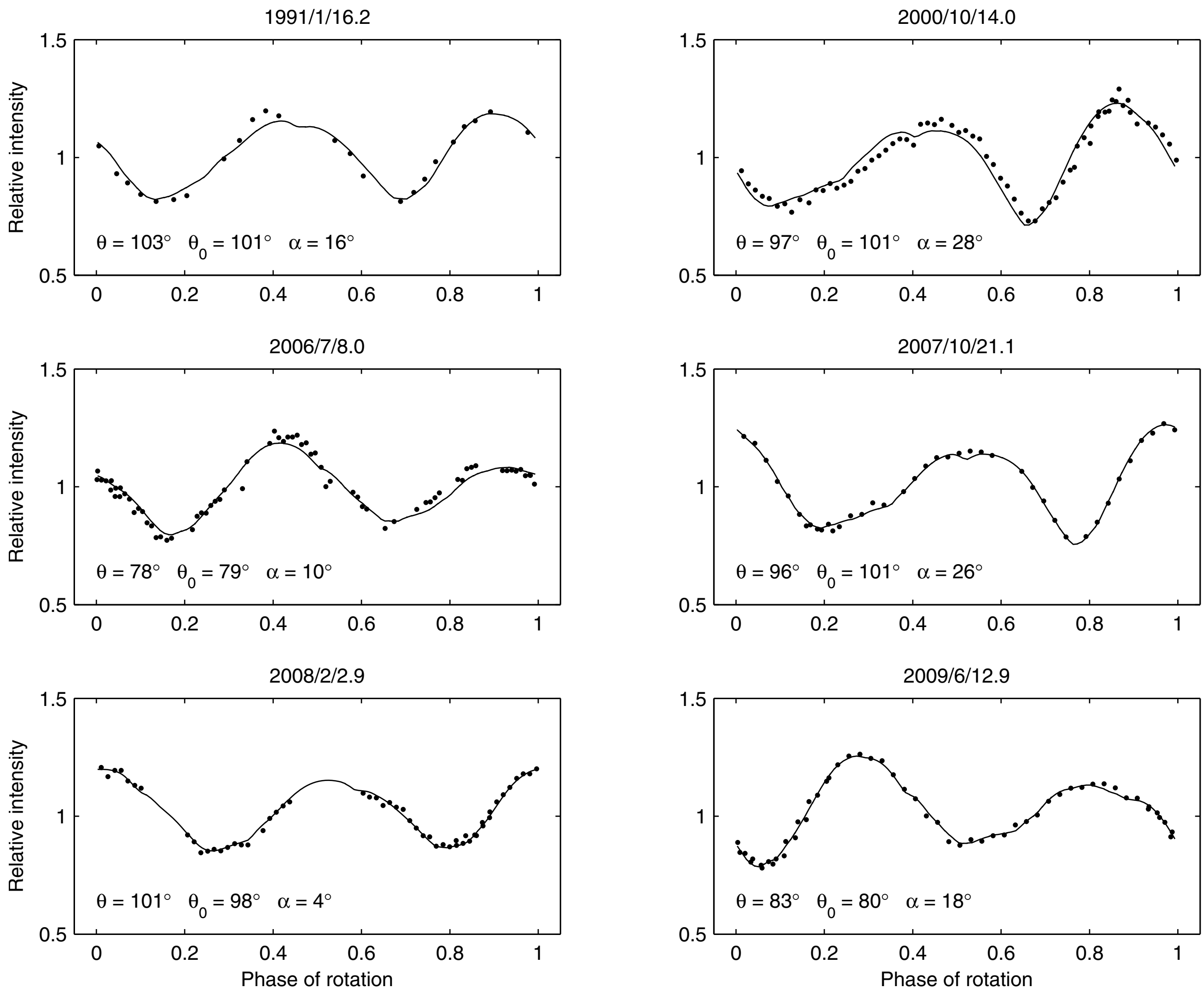

Fig. 2. Examples of Datura's lightcurves (symbols) fitted with our model (solid curve). The viewing and illumination geometry is given by the aspect angle θ, the solar aspect angle θ_0, and the solar phase angle α.

Yarkovsky-O'Keefe-Radzievskii-Paddack (YORP) effect, could only have changed rotation period by a few per-mil fractionally (see, e.g., Čapek & Vokrouhlický 2004). The situation is, however, different for the obliquity value.

The pole solutions P1 and P2 have current obliquities ~11.2° and ~15.3°, respectively, measured with respect to the orbital plane. While the YORP effect may have changed the obliquity by only a fraction of a degree (e.g., Čapek & Vokrouhlický 2004; Bottke et al. 2006), its initial value can hardly be inferred because of the parameter-dependent interplay of the gravitational torque due to the Sun and inertial torques due to moving orbital plane (known as the Cassini dynamics; e.g. Henrard & Murigande 1987; Vokrouhlický et al. 2006). To verify this conclusion, we used the symplectic numerical scheme of Breiter et al. (2005) to propagate the current rotation state (pole P1 and P2) for 1 Myr into the future. The orbit of Datura was propagated using the `SWIFT_MVS` integrator with a timestep of 5 d

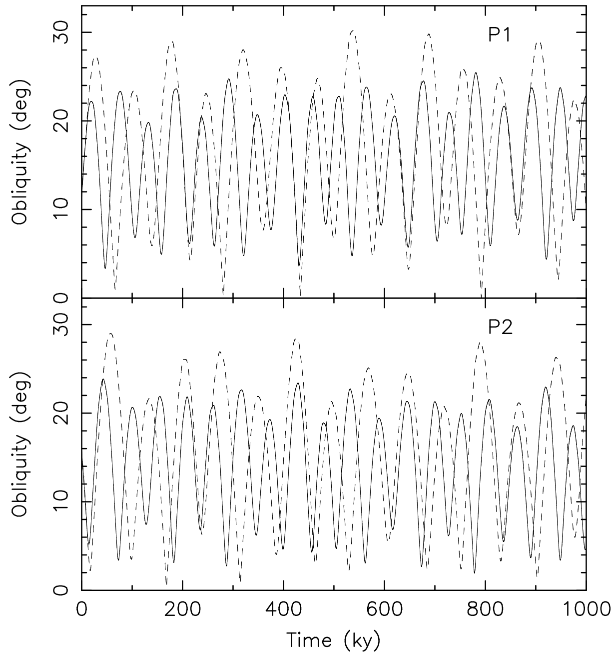

Fig. 3. Obliquity of P1 (*top*) and P2 (*bottom*) solutions during the next 1 Myr time interval. Numerical model includes gravitational torque from the Sun and evolution of Datura's orbit due to planetary perturbations. The solid lines are for $\Delta = 0.2$ value, the dashed lines are for $\Delta = 0.3$ value, of the asteroid's dynamical flattening.

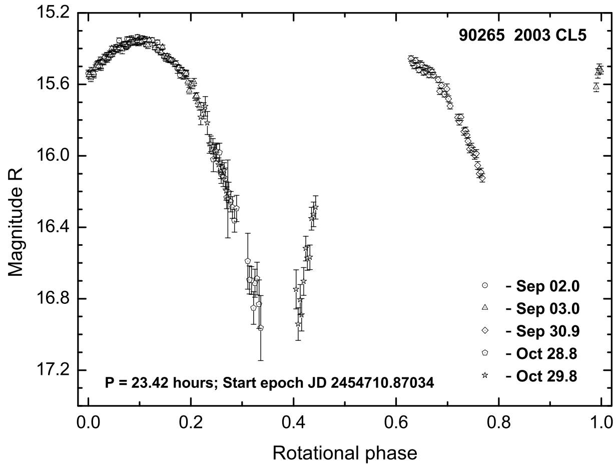

Fig. 4. Composite lightcurve of (90265) 2003 CL5 from the 2008 opposition. Different symbols for observations during 5 nights in September and October as indicated in the labels. The ordinate is the calibrated magnitude in standard R band; the calibrated observations were related using the H-G fitted phase curve assuming $G = 0.2$ value. We used 23.42 ± 0.02 h rotation period to transform all data into the phase of the rotation cycle (abscissa; zero phase at JD 2 454 710.87034).

and output sampling of 50 yr (the asteroid initial data from Table 1 and planetary ephemeris from JPL DE405), and then used by the Breiter et al. scheme to propagate the spin state. The only unknown parameter is the asteroid's dynamical flattening $\Delta = (C - 0.5(A + B))/C$, where (A, B, C) are the principal moments of inertia of the body. We used our two shape models for Datura associated with the P1 and P2 solutions, assuming a homogeneous distribution of density, to infer that Δ ranges from $\sim$0.15 to $\sim$0.3 (note that the lightcurve inversion method provides a reasonable shape of the body but only poorly constrains its Δ value).

Figure 3 shows the future obliquity evolution of the current pole positions P1 and P2 for the two assumptions of Δ: 0.2 solid curve and 0.3 dashed curve. In either of these two cases, the obliquity undergoes large amplitude oscillations up to $\sim 30°$ with Δ-dependent periodicity. For instance, in the $\Delta = 0.2$ case the principal period of the obliquity change is $\sim$54 kyr, significantly larger than the principal nodal precession period of $\sim$35 kyr. This difference, and the overall large amplitude of the obliquity oscillation, are related to significantly high obliquity value of the forced Cassini state 2 (e.g., Henrard & Murigande 1987; Vokrouhlický et al. 2006). For instance in the $\Delta = 0.2$ case, the forced Cassini state 2 is at $\sim 8.3°$ and becomes larger than $\sim 11°$ for $\Delta = 0.3$.

Figure 3 shows that the period, and thus also a phase, of obliquity oscillations critically depends on the unknown Δ value. Because the lightcurve inversion only poorly constrains Δ, the initial, post-breakup obliquity of Datura cannot be determined. It can be any value between zero and $\sim 30°$.

4. Rotation period for (90265) 2003 CL5

From the first night of observations, we were already able to infer that (90265) 2003 CL5 is a slow rotator. We then followed the object over five nights in September and October 2008. The composite lightcurve (Fig. 4) has a very large amplitude of 1.5 mag or more (because of the rotation period close to one day, our observations unfortunately did not cover any of the lightcurve minima). The insufficient coverage of the lightcurve prevents us from accurately determining the apparent rotational period during this opposition (we additionally note that the observing geometry somewhat changed in-between our first and last observations). One of the possible solutions, 23.42 ± 0.02 h, has been used in Fig. 4 to fold all observations into a single phase plot. There are, however, other possible solutions near this period.

Given the slow rotation rate and small size of (90265) 2003 CL5, it is interesting to explore the extent to which the YORP effect could have changed the rotation period within the estimated age of the Datura family. Using the statistical data in Čapek & Vokrouhlický (2004; Figs. 6–8), we estimate that the initial rotation period of this asteroid could not have been shorter than $\sim$17.5 h, while it could have been as long as $\sim$32 h. The shorter limit is perhaps more interesting, indicating that the initial rotation period of (90265) 2003 CL5 should have been fairly long in any case. We should also mention that the principal axis rotation of this asteroid, if confirmed by future observations, may provide an important constraint on the formation process after parent body fragmentation. We note that the canonical estimate for the damping timescale of an excited rotation state (e.g., Harris 1994) would give several hundreds of Myr, about a factor 100–1000 longer than the family age.

The very large amplitude of the lightcurve suggests an interesting possibility that this object is an extremely elongated, possibly bi-lobed object or even a close synchronous binary system[2]. We note that the hydrocode simulations of asteroid

[2] The long rotation period may support the model of a bi-lobed shape rather than a synchronous detached system. For example, if the binary system consisted of two spherical bodies with diameters 1 km and the bulk density 2 g/cm^3, the observed orbital period $\sim$24 hr would imply $\sim$3 km for the semimajor axis of the mutual orbit. Apparently, such a large relative separation is not consistent with the shape of the observed lightcurves. Assuming spherical components, the lightcurve amplitude also cannot be larger than $\sim$0.8 mag. Triaxiality of the components may however slightly change these conclusions.

fragmentation do predict large fraction of binary fragments, the so-called escaping ejecta binaries (e.g., Durda et al. 2004; Nesvorný et al. 2006b; Richardson et al. 2009). However, it seems that (90265) 2003 CL5 being a bi-lobed object (perhaps a failed binary) would challenge several current models. As a result, (90265) 2003 CL5 may provide interesting information about the fragmentation process of large asteroids in general, and our ability to model this particular asteroid numerically. This strongly motivates further photometric observations of this system in the future. In particular, it is important to obtain calibrated observations that would allow us to unambiguously link all available data and cover lightcurve minima that were not seen in our 2008-opposition data.

Unfortunately, (90265) 2003 CL5 will be quite faint during the 2010 opposition such that small- and medium-scale telescopes will not allow us to continue its photometry. The next truly favorable observing conditions for this asteroid will occur in June and July 2011. Interestingly, at this opposition the ecliptic longitude of the asteroid will span values between 260° and 270°, suitably complementary to those in 2008 (Table 3). As a result, observations from this opposition may themselves help to exclude some pole positions, even though not yet able to determine the pole accurately.

5. Re-estimation of Datura family age

In a first attempt to reconstruct the Datura cluster past configuration, and thus infer its age, Nesvorný et al. (2006b) used orbits of four members of the family. Out of these, only (1270) Datura had very precisely determined orbital elements. Orbits of the other three asteroids – (60151) 1999 UZ6, (90265) 2003 CL5 and (203370) 2001 WY35 – were significantly less accurate, reflecting the small number of available astrometric observations over short time intervals of only 6 to 8 years. Since then, the situation has significantly improved.

First, Sergio Foglia and colleagues made a significant effort attempting to find young-families' members on archival plates and succeeded in several cases. For instance, discovery of (90265) 2003 CL5 on the NEAT program archival frames taken in January 1996 allowed us to extend the known orbital arc of this asteroid by several years into the past. Second, the discovery of the young families allowed us to prompt targeted astrometry observations to ensure that most of the objects are observed on every subsequent opposition. In this respect, we should point out in particular observations made with the 1.5 m telescope at Mt. Lemmon Observatory at the Catalina Sky Survey (CSS). Importantly, both lines of effort led to precovery and recovery of the Datura member (215619) 2003 SQ168 nearly simultaneously in December 2007. Since then, CSS also acquired astrometry of this object in April and May 2009 during its next opposition. As a result, we can now use this asteroid for the past reconstruction of the Datura cluster. The information about the currently available accuracy of the orbits of Datura members is given in Table 1 (compare with Table 1 in Nesvorný & Vokrouhlický 2006).

We used the same approach as Nesvorný et al. (2006b) and Nesvorný & Vokrouhlický (2006) to determine the past orbital configuration of the Datura members. We refer interested readers to these references for details, limiting ourselves here to a minimal description of the technique. We considered a large number of statistically identical orbital clones for the asteroids. This was necessary because the past orbital history of each of the members depends on: (i) the current orbital uncertainty (Table 2); and (ii) unknown physical parameters. The former simply means that we have to take a number of initial orbital data for the backward integration uniformly filling the uncertainty ellipsoid in the orbital element space (we call them geometric clones). The second refers to the thermal (Yarkovsky) forces that may significantly affect the orbital evolution over timescales of tens to hundreds of thousands of years and that depends on the spin state and surface properties of the body (e.g., Bottke et al. 2006). Therefore, we need to uniformly cover a range of possible past evolutions of the orbits with Yarkovsky forces applied. We call these variants the Yarkovsky clones.

Performing backward integrations[3] of the clone versions for each of the asteroids, we can now at each time choose at random their identification to construct one possible cluster configuration. Given the large number of integrated clones, many of these identifications are possible and we can only characterize information about their proximity on a statistical basis. To work quantitatively, we define a target function[4] (e.g., Nesvorný & Vokrouhlický 2006)

$$\Delta V = na\,\sqrt{k_1\,\left(\sin i\,\Delta\Omega\right)^2 + k_2\,\left(e\,\Delta\varpi\right)^2}, \qquad (1)$$

where (a, e, i) are the orbital elements of the largest asteroid in the family, n its heliocentric mean motion, $k_1 = 1$ and $k_2 = 1/2$ and the node and pericenter dispersions are defined by $(\Delta\Omega)^2 = \sum_{ij}(\delta\Omega)^2_{ij}/N_{ij}$ and similarly for the pericenter. We sum over all possible independent pairs of the asteroids in the particular identification of the family. For instance, using 6 members of the family, the i and j indexes range from 1–6 and $N_{ij} = 15$. The target function in Eq. (1) reflects that the Datura members are sufficiently close in terms of (a, e, i) elements and basically probes sufficient convergence of the secular angles Ω and ϖ. Its structure also follows from the analysis of the Gauss equations of the perturbation calculus (e.g., Bertotti et al. 2003; Nesvorný & Vokrouhlický 2006) and can be interpreted in terms of the characteristic fragment dispersal velocity. As a rule of thumb, we expect the acceptable solutions to imply/infer a value of ΔV of the order of the escape velocity from the estimated parent body of the family, some ∼5−10 m/s.

The integration of thousands of clones with dense enough time output becomes computationally difficult, both as far as CPU time and disk space are concerned. For that reason, we adopted the following approximation:

- the past orbital evolution of (1270) Datura is represented by 30 geometric clones, each of which has additionally 15 Yarkovsky clones with $\mathrm{d}a/\mathrm{d}t$ value negative (this is because we integrate into the past and <90° obliquity for Datura guarantees the sense of its migration due to the thermal forces), implying that altogether we have 450 geometric and Yarkovsky clones;
- the past orbital evolution of (60151) 1999 UZ6, (90265) 2003 CL5, and (203370) 2001 WY35 is represented

[3] We use `SWIFT_MVSY` symplectic integrator (e.g., Brož 2006) with all planets included and timestep of 5 days. The initial state vectors for planets were obtained from JPL DE405 ephemerides at the same time as the elements of the Datura-cluster asteroids (Table 1). We use rather dense output sampling of 20 yr and integrate backward in time till 700 kyr.

[4] To see if our results are robust, we also evaluated another target function $\Delta V'$, defined as in Eq. (1), where $\Delta\Omega$ and $\Delta\varpi$ are performed with respect to the orbit of (1270) Datura only and the summation is performed over the remaining members in the cluster. As such, the $\Delta V'$ quantity measures dispersal velocity field of the Datura-family fragments with respect to the largest fragment. Note the ΔV target function may become unrealistically small for a cluster of fragments that reside on nearby orbits, yet distant from the largest asteroid in the family.

by 30 geometric clones, each of which has additionally 30 Yarkovsky variants, so altogether there are 900 geometric and Yarkovsky clones;
- the past orbital evolution of (89309) 2001 VN36 and (215619) 2003 SQ168 is represented by 40 geometric clones, each of which has in addition 40 Yarkovsky variants, and altogether there are 1600 geometric and Yarkovsky clones.

A few comments are in order. First, it appears unnecessary to consider so many clone variants for the largest asteroid (1270) Datura. For instance, the estimated nodal variation caused by mismodeled Yarkovsky forces $\Delta\Omega \sim 0.5\,(\partial s/\partial a)\,(\Delta a)\,T$ (and similarly for the longitude of pericenter) is $\sim 0.02^\circ$ or less. Here s is the proper frequency of node precession for which we have $(\partial s/\partial a) \simeq -38$ arcsec/yr/AU in the Datura zone (e.g., Vokrouhlický et al. 2008), $\Delta a \sim 10^{-5}$ AU is an estimate of the maximum accumulated Yarkovsky change in the semimajor axis a in the timespan $T \sim 500$ kyr (see, e.g., Bottke et al. 2006, for characteristic rates of change in a for asteroids in the main belt). This small influence of the Yarkovsky clones is due to Datura's large size; the similar effect may be an order of magnitude larger for smaller members in the family. However, by tracking a limited number of geometric clones we found that the underlying chaoticity of the Datura region may still cause the pure geometric clones disperse in node and pericenter by up to $\sim 0.1^\circ$, more than the above estimated Yarkovsky contribution. This test showed the necessity of including some limited number of geometric and Yarkovsky clones even for (1270) Datura. Second, the larger number of clones for (89309) 2001 VN36 and (215619) 2003 SQ168 obviously compensates for the larger uncertainty of their past orbital configuration. In the case of (89309) 2001 VN36, this is because of its interaction with the 9/16 exterior resonance with Mars (e.g., Nesvorný & Vokrouhlický 2006, Fig. 1). Indeed, tracking the possible past evolution of the geometric clones for this body, we noted that they can disperse on average by $\sim 2^\circ$ in ~ 500 kyr, with the most distant clones being up to $\sim 5^\circ$ away in node and pericenter. The large number of clones for (215619) 2003 SQ168 is obviously due to having the most poorly constrained orbit of all Datura members (except for the unused orbit of 2003 UD112) and its small size.

When all six asteroids are included, the past Datura cluster reconstruction is in our integration represented by as many as $450 \times 900^3 \times 1600^2 = 8.4 \times 10^{17}$ clone identifications. This number surpasses by far CPU possibilities to evaluate target functions ΔV and $\Delta V'$ for each one of these identifications at each output from our integrations (20 yr in our case). We thus only compute the target functions for randomly chosen 50 million different identifications at each output step. This is much less than the maximum possible number of clone combinations and may imply that we significantly undersample the results. Fortunately, the situation is improved by several factors: (i) clones of (1270) Datura and (90265) 2003 CL5 have far more similar past evolutions than other bodies; (ii) the close nodal/pericenter configuration, for which the target functions ΔV and $\Delta V'$ remain smaller than some threshold, may last up to 20 kyr, a factor 10^3 longer than our output sampling of 20 yr; and (iii) not all clones have widely different past orbital evolutions. Taking these factors into consideration, we estimate that the 50 million trial identifications at each time output should be sufficiently representative.

Table 1 also indicates that orbits of (1270) Datura and (215619) 2003 SQ168 are very close to each other (including the mean longitude in orbit). For that reason, the two objects were assumed to be paired objects. Vokrouhlický & Nesvorný (2008) argued against this possibility, proposing instead that an anomalously small initial separation of (215619) 2003 SQ168 from (1270) Datura caused their current proximity[5] (see Fig. 6 in Vokrouhlický & Nesvorný 2008). If well constrained, the convergence of the two orbits in the mean anomaly value might then be used as an additional criterion for the age determination of the Datura family. Unfortunately, the present orbital uncertainty of (215619) 2003 SQ168, and lack of knowledge of its physical parameters, prevents this kind of approach. The Yarkovsky clones of this small asteroid diverge in the mean longitude in orbit by $\delta\lambda/2\pi \simeq (3/4)\,(T/P_{\rm orb})\,(\Delta a/a)$ after time T; here $P_{\rm orb} \simeq 3.34$ yr is the heliocentric revolution period and Δa is the accumulated change in semimajor axis a due to the Yarkovsky effect in time T. For $T \simeq 500$ kyr, and the estimated size of (215619) 2003 SQ168, we have $\Delta a \simeq 10^{-4}$ AU. We thus note that after only ~ 100 kyr the Yarkovsky clones extend along the entire elliptic orbit and prevent any deterministic work using the mean anomaly value.

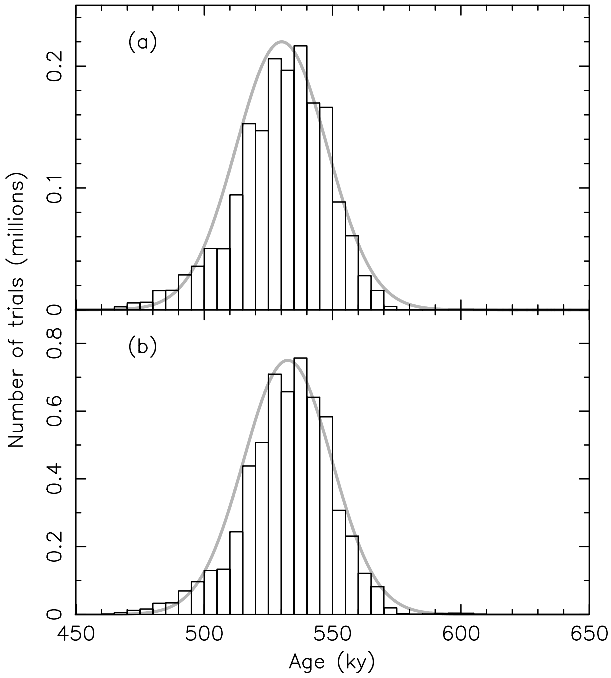

Fig. 5. Number of clone combinations that provided target functions smaller than 5 m/s: (i) ΔV from Eq. (1) (part **a**), *top*), and (ii) $\Delta V'$ (part **b**), *bottom*). Data were collected into 5 kyr wide bins. The Gaussian curves in grey are for illustration purposes only: (i) 530 kyr mean value and 18 kyr standard deviation at the *top panel*; and (ii) 532 kyr mean value and 17 kyr standard deviation at the *bottom panel*. At each 20 yr spaced output, we run 50 million trial configurations of all available Datura asteroids, except for the single-opposition case of 2003 UD112 (Table 1).

5.1. Results

Figure 5 shows distribution of age values determined by a number of the clone combinations corresponding to target functions ΔV from Eq. (1) (upper panel) and $\Delta V'$ (lower panel) smaller than 5 m/s, rather restrictive value. All Datura asteroids, except obviously the single-opposition case of 2003 UD112, and 50 million trial identifications of different clones at each time

[5] In this paper, we take this standpoint and do not investigate the less likely possibility that (215619) 2003 SQ168 separated from (1270) Datura in a more recent epoch.

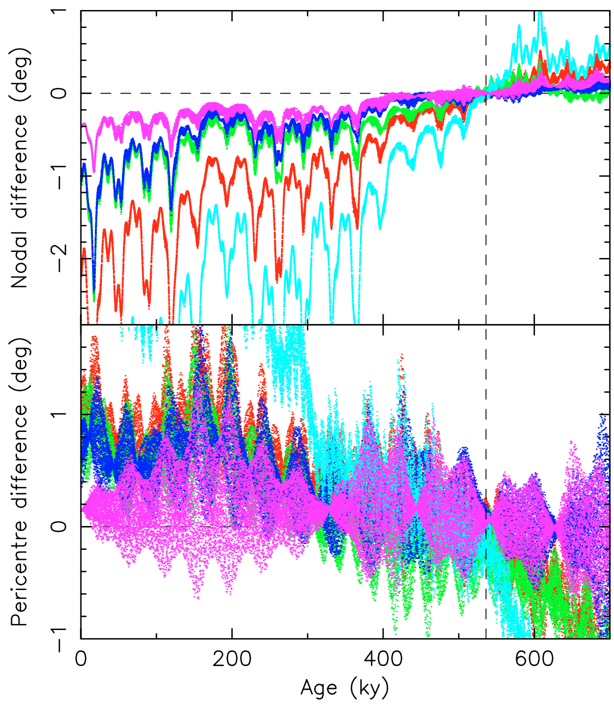

Fig. 6. An example of a good convergence of secular angles for the Datura family members. *Upper and lower panels* show past difference of longitude of node and longitude of pericenter with respect to (1270) Datura, the largest asteroid in the family, for: (90265) 2003 CL5 [red], (60151) 1999 UZ6 [green], (203370) 2001 WY35 [blue], (89309) 2001 VN36 [cyan] and (215619) 2003 SQ168 [magenta]. The vertical dashed line denotes the best convergence time 536 kyr for which $\Delta V = 1.4$ m/s in this case.

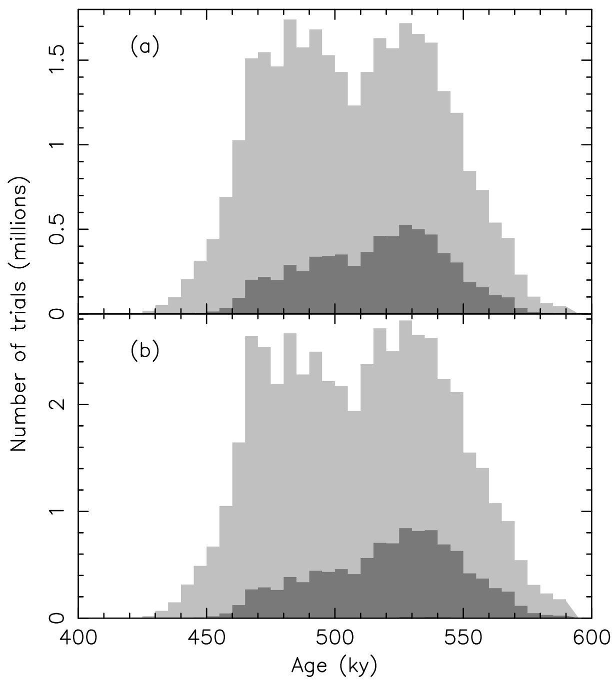

Fig. 7. Number of clone combinations that provided target functions smaller than 13 m/s (light grey histogram) and 10 m/s (dark grey histogram): (i) ΔV from Eq. (1) (part **a)**, *top*), and (ii) $\Delta V'$ (part **b)**, *bottom*). Data were collected into 5 kyr wide bins. In this case only half a million trials of the clone identifications was used at each output from the simulation.

have been used in this analysis. The age distribution is matched satisfactorily by a Gaussian (grey curves) with mean values of 530 kyr and 532 kyr, respectively, and standard deviations both of ~18 kyr. Figure 6 illustrates possible past convergence of the secular angles as referenced to the (1270) Datura value for a good solution that has $\Delta V = 1.4$ m/s some 536 kyr ago. This result comes as a surprise, because it deviates significantly from the solution of Nesvorný et al. (2006b) and increments the previously determined age of the Datura family by nearly 100 kyr. This disagreement in the two solutions requires some explanation and/or analysis and that prompted us to perform several further tests[6].

First, we tested how the solution depends on the chosen threshold for the target function values, increasing it to 10 m/s and 13 m/s. Resulting age distributions are shown in Fig. 7. Because there are many more possible solutions now, we performed only half a million trials of the clone identifications in this case. Indeed, we observe that the possible age solutions now extend to smaller values more compatible with the result of Nesvorný et al. (2006b). However, we would consider the 13 m/s cutoff not to provide a strong constraint and this is also reflected in the numerous solutions found: even if we restricted ourselves to 50 thousand trials (out of the theoretical maximum value 8.4×10^{17}), we would obtain many solutions. The 13 m/s value translates indeed into a mean quadratic nodal or pericenter distance of nearly $\Delta\Omega \simeq 0.2°$. Past orbital evolutions in Fig. 6 hint that this is rather easily matched over a long interval of time.

[6] Obviously, the two age determinations used different orbit sets and this might have influenced the results. However, if the new observations caused simple shrinking of the uncertainty ellipsoid in the space of initial orbital elements, we would expect to obtain equally nested solutions: the one with more accurate orbits would be entirely within the one with less accurate orbits. This idea assumes uniform mixing of results from the uncertainty ellipsoid, which is likely, but not entirely guaranteed.

To determine more exactly the sources of difference between the two solutions, we neglected the orbital history of (89309) 2001 VN36 from our simulation. This approach was adopted by Nesvorný et al. (2006b) because the orbit of this asteroid was assumed to be too uncertain because of resonance-related chaoticity. Performing again half a million random identifications at each time instant in the past, as given by our numerical propagation, we obtained results shown in Fig. 8. While the bulk of the distribution shifted toward the 450 ± 50 kyr solution interval determined by Nesvorný et al. (2006b), there is an extension beyond its 500 kyr age. Choosing a limited amount of trials and effective high-cutoff values for the target functions, one may preferentially find the optimal age solutions in the 450 ± 50 kyr interval and we believe that this is what happened. Decreasing the cutoff limit again to 5 m/s for the target functions, the Datura age indeed moves beyond half a million value even in this simulation where the highly-chaotic orbit of (89309) 2001 VN36 was excluded.

To summarize, our main conclusions are that: (i) if we are not overly optimistic, our analysis suggests an age in between 450 and 600 kyr for the Datura cluster; and (ii) if we were to take our most complete and restricted solution for granted, the cluster age would decrease within the 530 ± 20 kyr interval. This is where, effectively, the best-convergence solutions reside. More work appears to be required to resolve the issue of the Datura cluster age. This includes both new astrometric and physical observations (that would constrain the possible diverse Yarkovsky

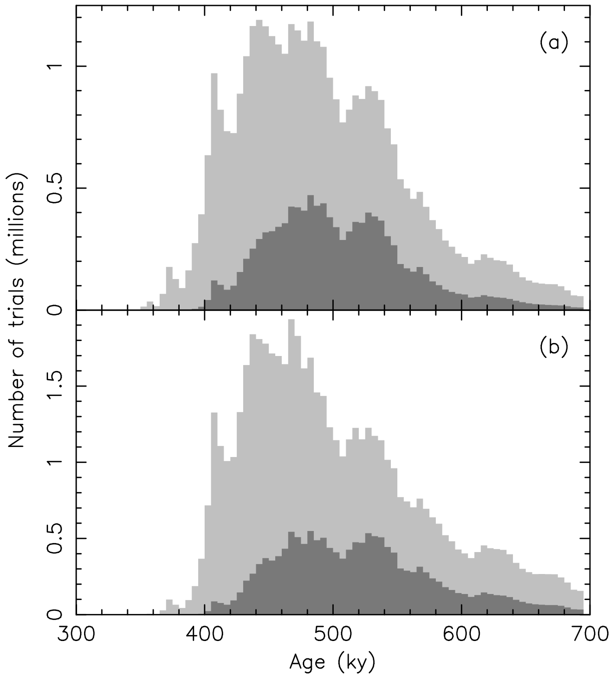

Fig. 8. Number of clone combinations that provided target functions smaller than 13 m/s (light grey histogram) and 10 m/s (dark grey histogram): (i) ΔV from Eq. (1) (part **a**), *top*), and (ii) $\Delta V'$ (part **b**), *bottom*). Data were collected into 5 kyr wide bins. Past orbital history of (89309) 2001 VN36 was not included in this analysis and half a million trials of the clone identifications were used at each output from the simulation.

histories for small Datura members), but perhaps also more sophisticated theoretical methods than used so far.

6. Conclusions

This paper has presented our state-of-art knowledge of the Datura asteroid family at the dawn of the upcoming new-generation surveys such as PanSTARRS or LSST (e.g., Jedicke et al. 2007; Ivezić et al. 2007). It will be interesting to see how many more Datura-family members will be discovered in the next few years. Input from these new datasets seems crucial, because with the current instrumentation no additional Datura members have been found since the discovery of the family in late 2005 (the last three members were discovered in 2003). On the other hand, we argue that it is equally important to continue with further astrometric and photometric observations of the fainter, currently known members. This is because the newly discovered asteroids will likely be very small, ≲2 km, and the lack of spin state information will make their past orbits uncertain primarily due to unconstrained Yarkovsky forces. As a result, continuing photometric observations of the known members may help us to constrain at least the sense of their rotation and thus eliminate many of the clones used in the age determination simulations in Sect. 5.

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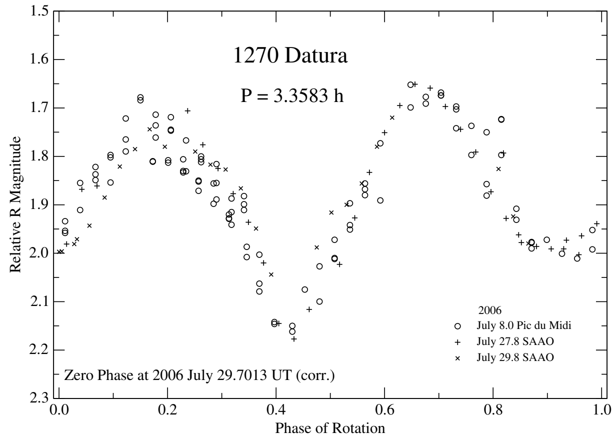

Fig. A.1. Composite lightcurve of (1270) Datura during the 2006 apparition.

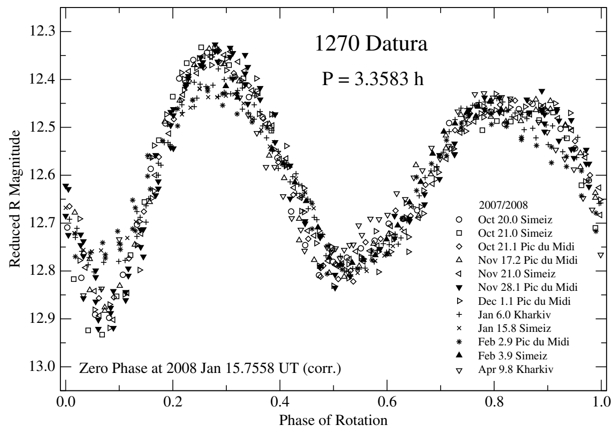

Fig. A.2. Composite lightcurve of (1270) Datura during the 2007/2008 apparition. Lightcurves obtained in January-February 2008 have smaller amplitudes since the phase angles were smaller (see Table 2). In the same way, the largest spread corresponds to the observations from beginning and end of the opposition because they were taken with slightly different viewing geometry.

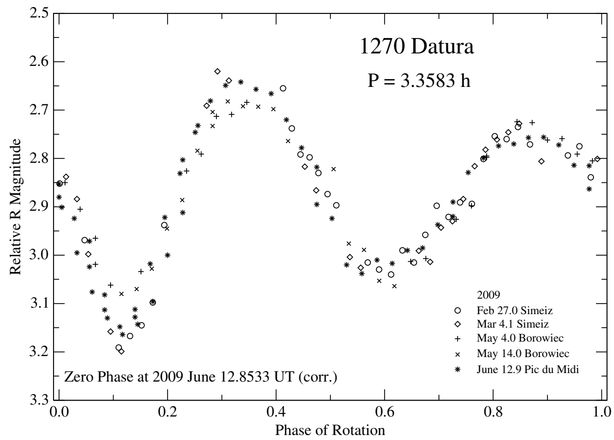

Fig. A.3. Composite lightcurve of (1270) Datura during the 2009 apparition.

Appendix A: Composite lightcurves and phase function for (1270) Datura

In this Appendix, we present composite lightcurves of (1270) Datura containing all our new observations starting from the

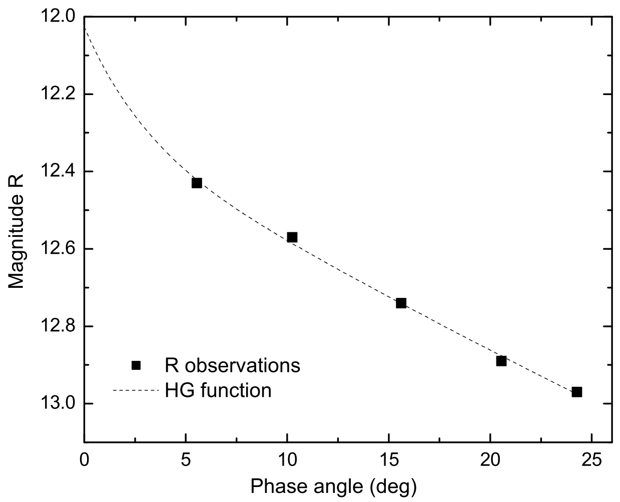

Fig. A.4. Solar phase angle behavior for (1270) Datura derived from our R band calibrated observations (symbols). The dashed curve is the best-fit model using $H_0 = 12.03 \pm 0.02$ and $G = 0.29 \pm 0.01$.

2006 apparition (Figs. A.1–A.3). We also show the phase curve for this asteroid using our calibrated R and V band observations and the corresponding fit in the $H - G$ system (Fig. A.4). Our best-fit model values are $H_0(R) = 12.03 \pm 0.02$, at the maximum of the lightcurve, and $G(R) = 0.29 \pm 0.01$. We used data from 1991 (Wisniewski et al. 1997; with the derived $V - R$ value), 2007/2008 (Simeiz, Kharkiv) and 2009 (Simeiz), see Table 2.

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