(65803) Didymos

The 2017 observations and a preliminary update of the orbital model

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Photometric data for (65803) Didymos

Date (UT)	Telescope(s)	# Pts	V	RMS Res.
2003-11-20 to 24	Ond 0.65-m, CH 0.35-m, Mt. Lemmon 1.5-m	1111	12.9	0.008
2003-11-26 to 12-04	Ond 0.65-m, CH 0.35-m, PDO 0.50-m	778	13.2	0.008
2003-12-16 to 20	Ond 0.65-m, PDO 0.50-m	458	14.9	0.012
2015-04-13 to 14	DCT 4.3-m	87	20.6	0.024
2017-02-25.1	GTC 10.4-m	75	21.0	0.019
2017-02-25.5	MMT 6.5-m	137	21.0	0.032
2017-03-31.1	WHT 4.2-m	100	20.4	0.027[c]
2017-04-18.2	DCT 4.3-m	66	21.1	0.034[c]
2017-04-27.1	NTT 3.5-m	108	21.3	0.024

[c] affected by clouds

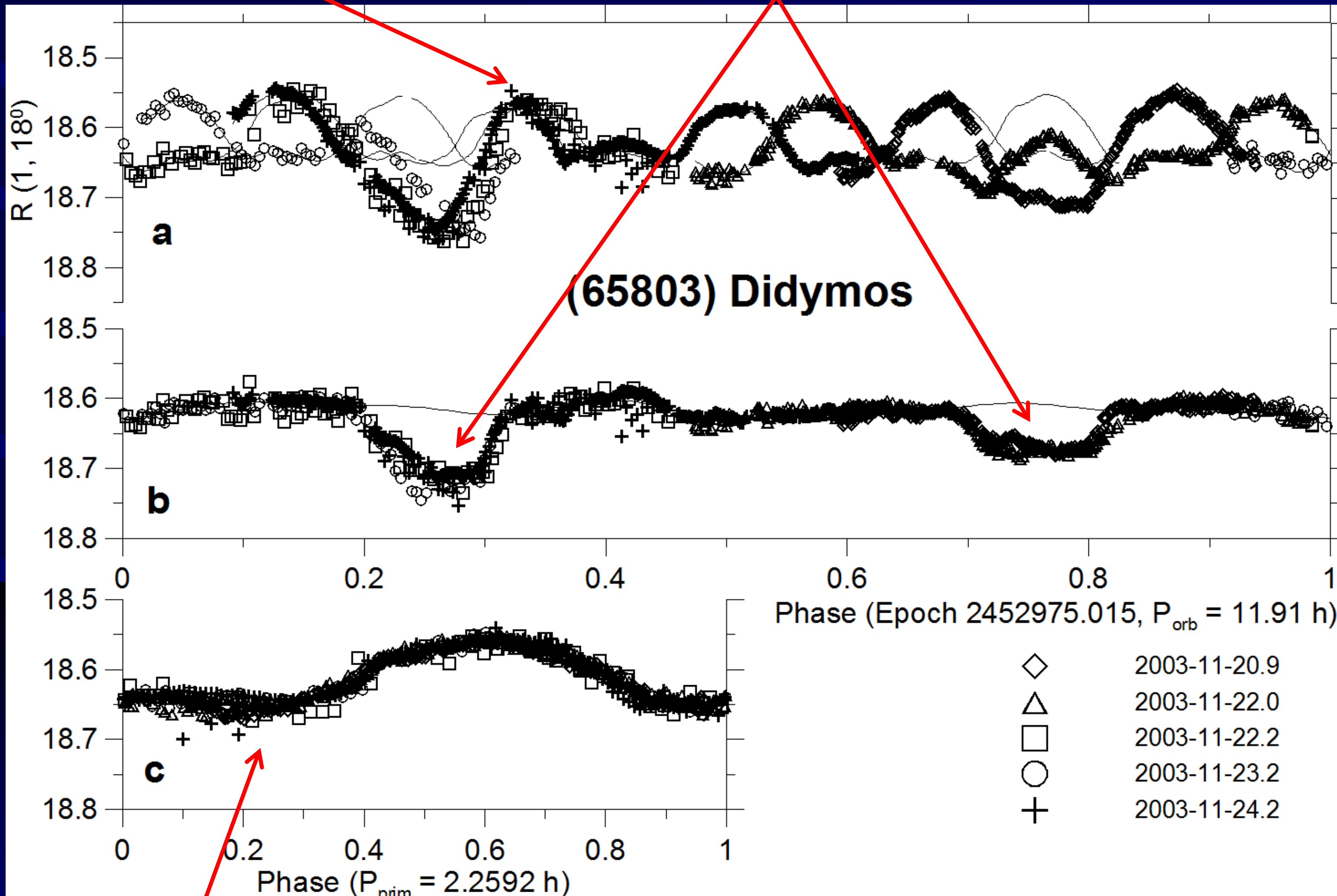
The 2017 data were observed and reduced by Colin Snodgrass, Ellen Howell, Simon Green, Audrey Thirouin and Javier Licandro.

A few more runs to be finished (reduction completed or refined).

2003 data (a)

Full lightcurve

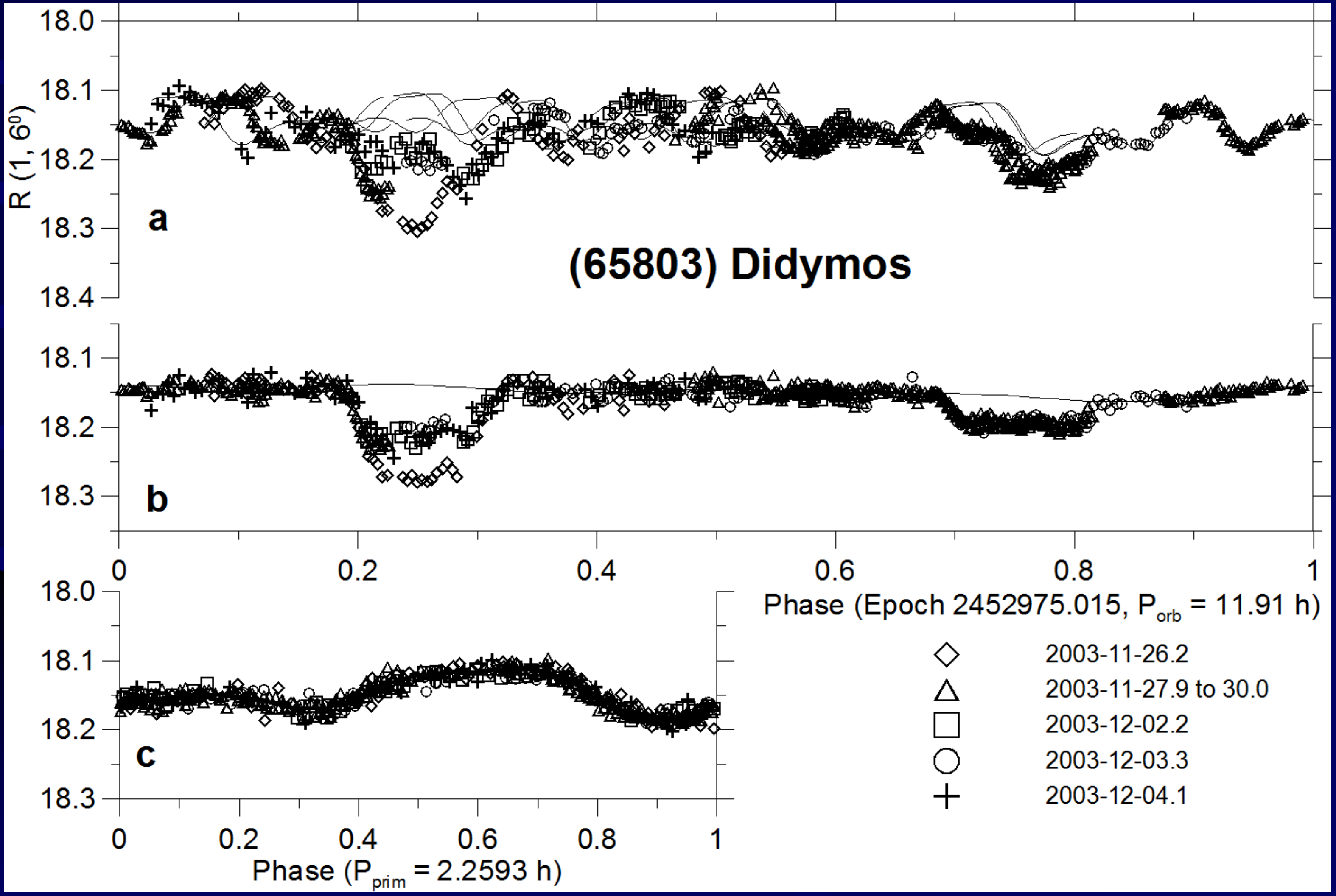
Mutual events (from l.c. decomposition)



Primary rotational lc (time axis stretched)

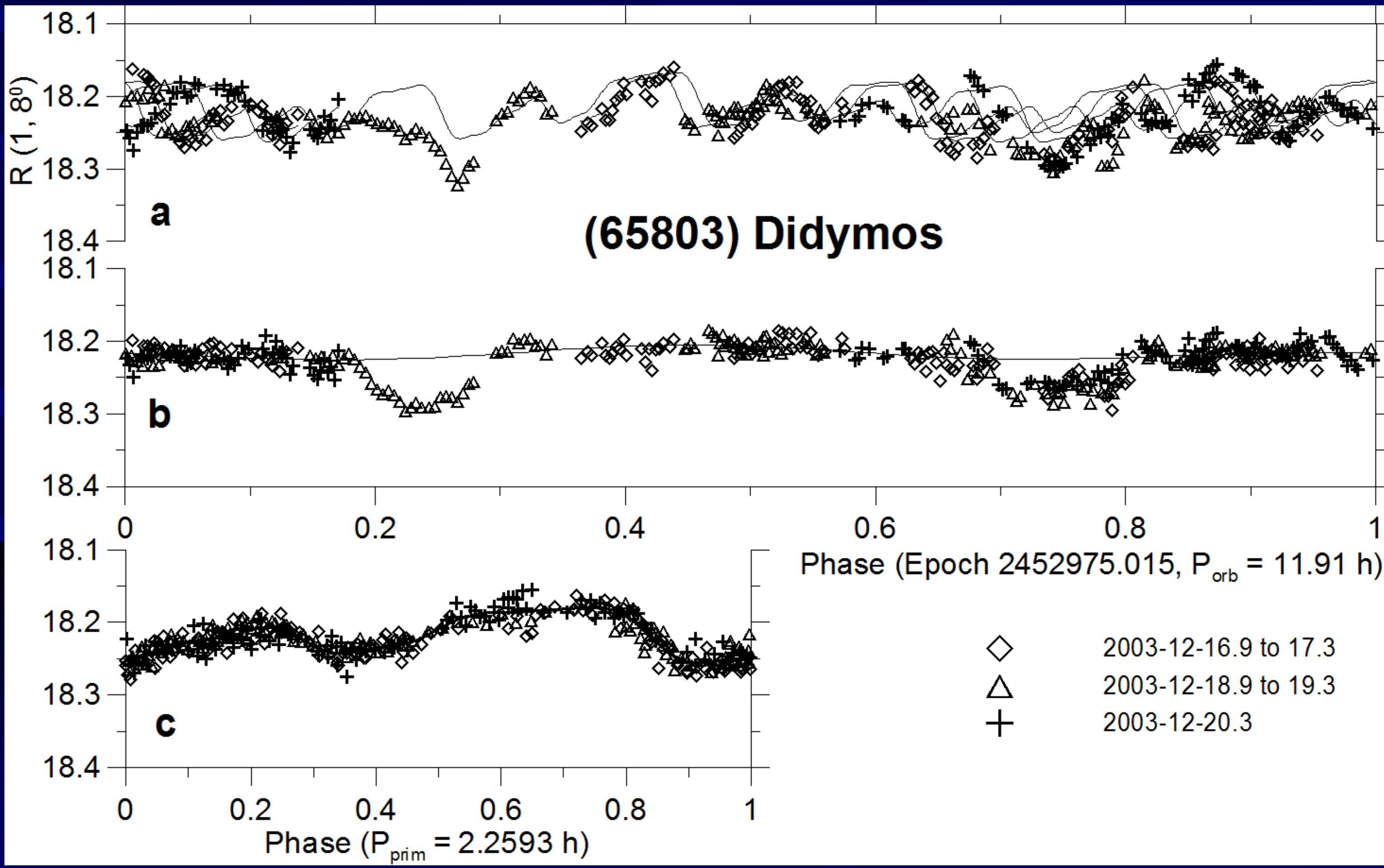
Pravec et al. (2006)

2003 data (b)



Pravec et al. (2006)

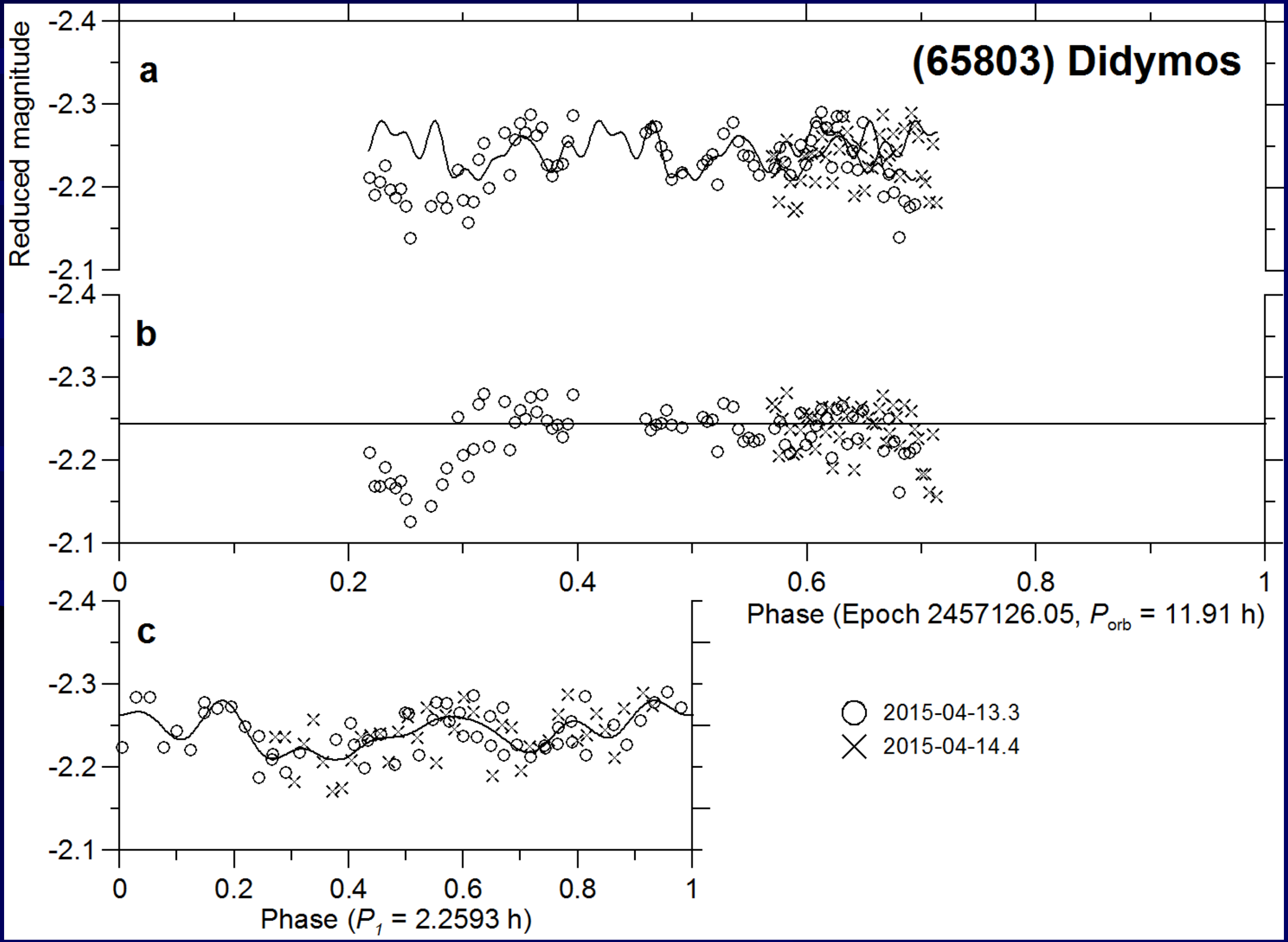
2003 data (c)



Pravec et al. (2006)

2015 data

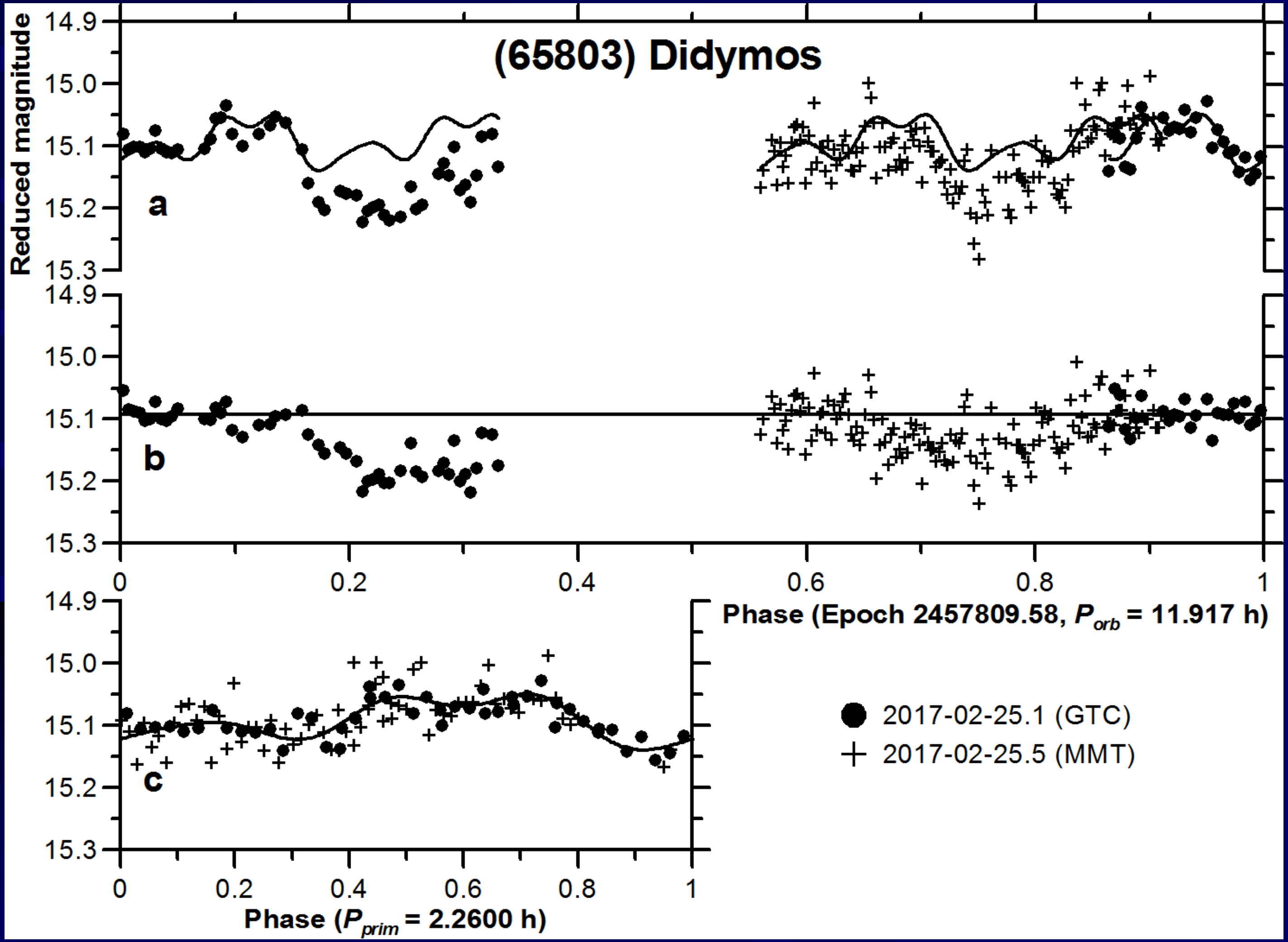
Discovery Channel Telescope 4.3-m



(Observed A. Thirouin, reduced P. Kušnirák and P. Pravec)

2017 data (a)

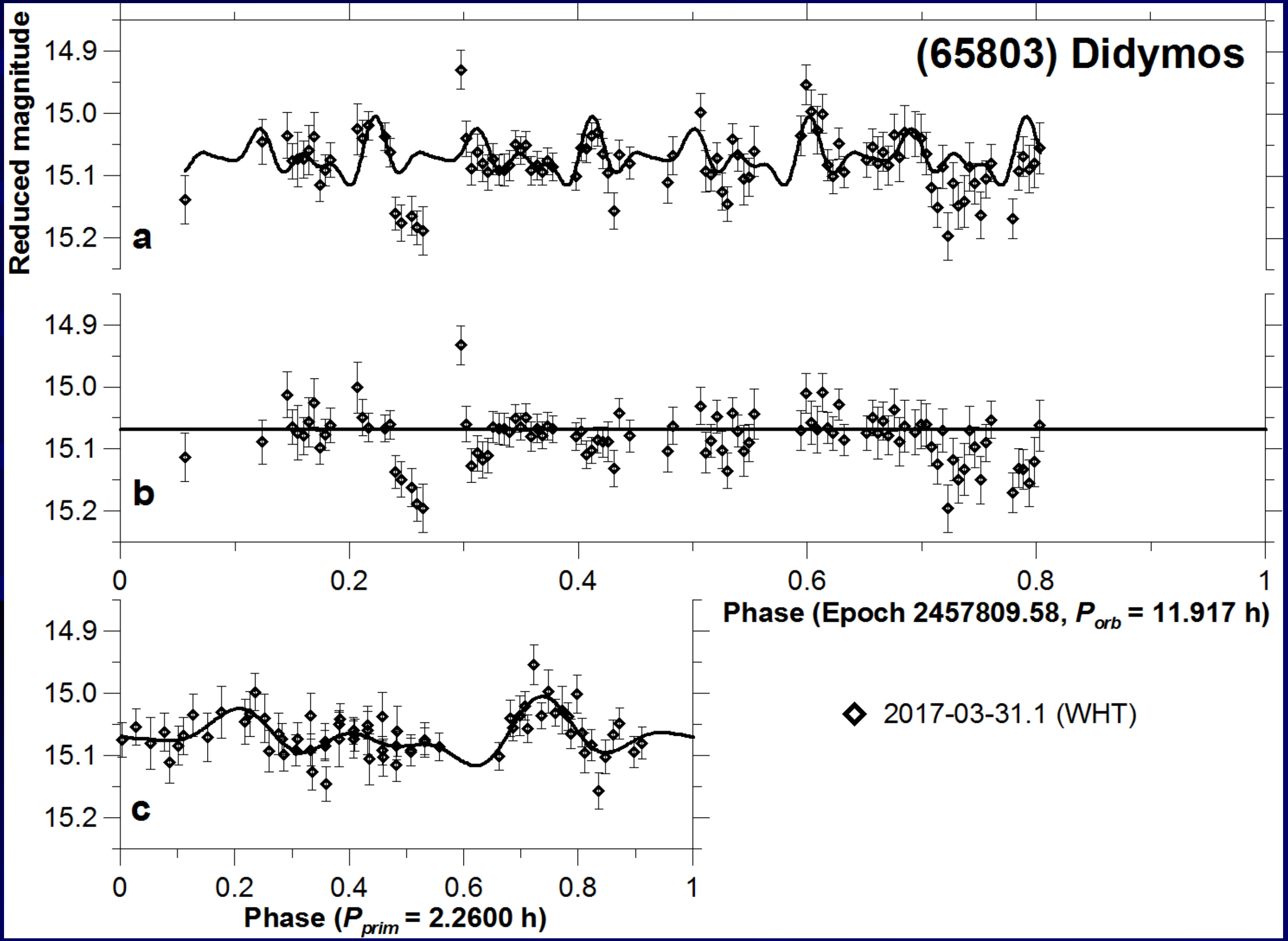
Gran Telescopio Canarias 10.4-m, Multiple Mirror Telescope 6.5-m



(Observed J. Licandro and E. Howell, reduced C. Snodgrass and E. Howell)

2017 data (b)

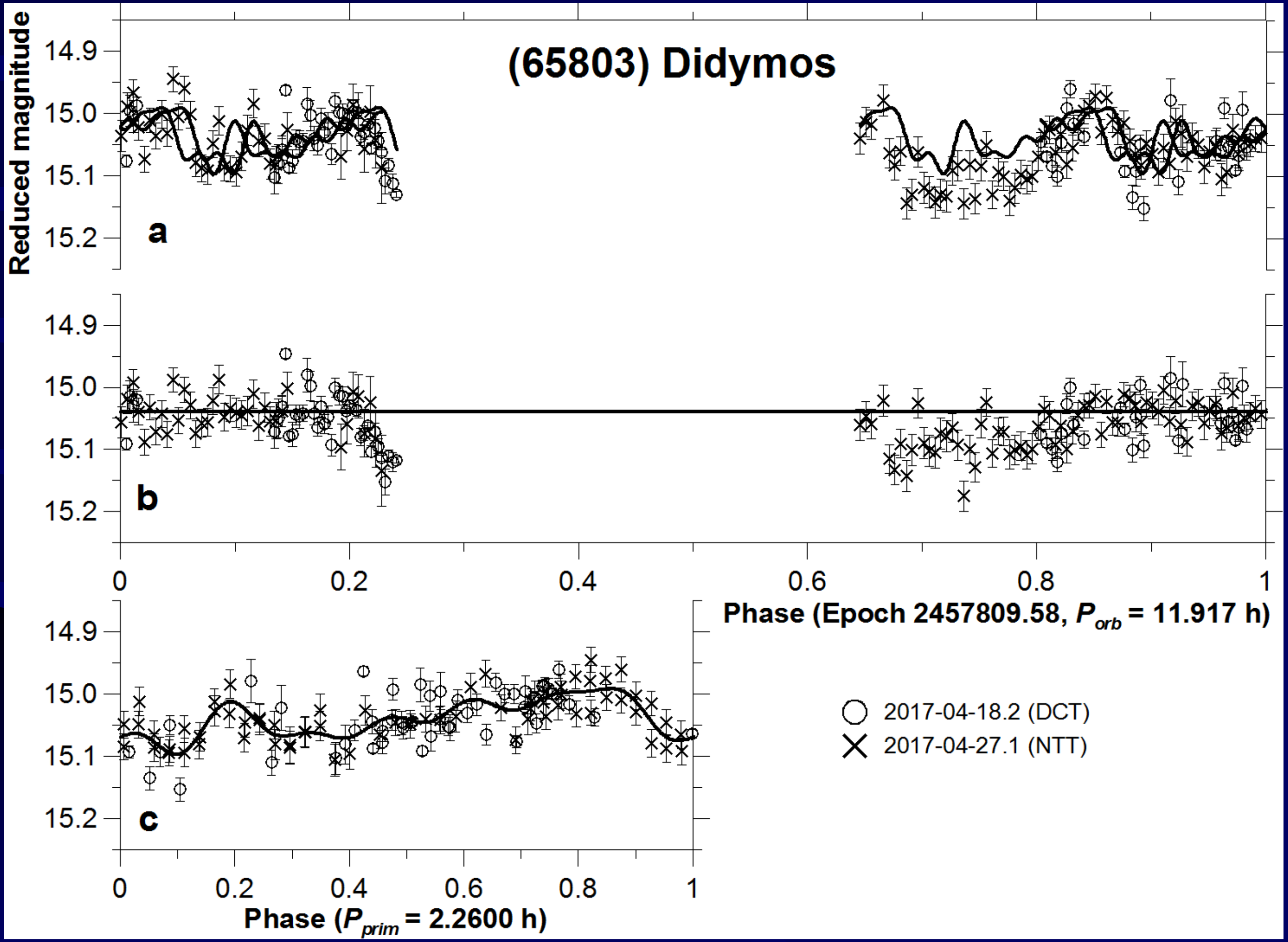
William Herschel Telescope 4.2-m



(Observed and reduced S. Green)

2017 data (c)

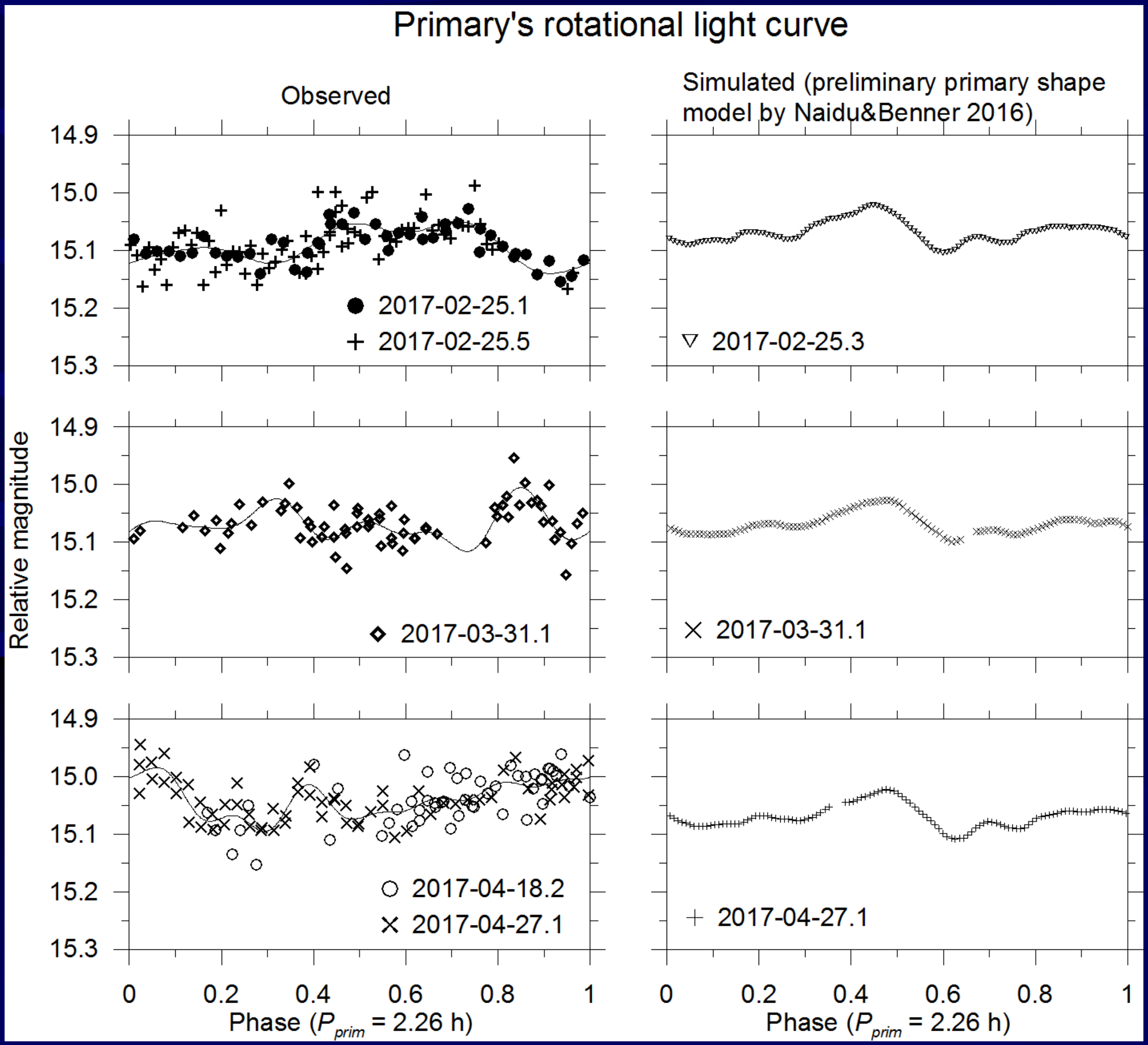
Discovery Channel Telescope 4.3-m, New Technology Telescope 3.5-m



(Observed and reduced A. Thirouin and C. Snodgrass)

Primary’s rotational light curve

Primary's light curve in 2017



Observed:
Amplitude 0.09-0.11 mag
Multiple maxima (conspicuous signal up to the 4th, 6th and 7th harmonic)
Changing on monthly scale

Simulated (using the Naidu & Benner 2016 preliminary shape model):
Amplitude 0.07-0.09 mag
One prominent maximum
Only small changes over the 2-month interval.

Similar misfit also for the 2015 light curve.

The primary shape model must be revised.

Orbital model

Preliminary update with the incomplete 2017 data

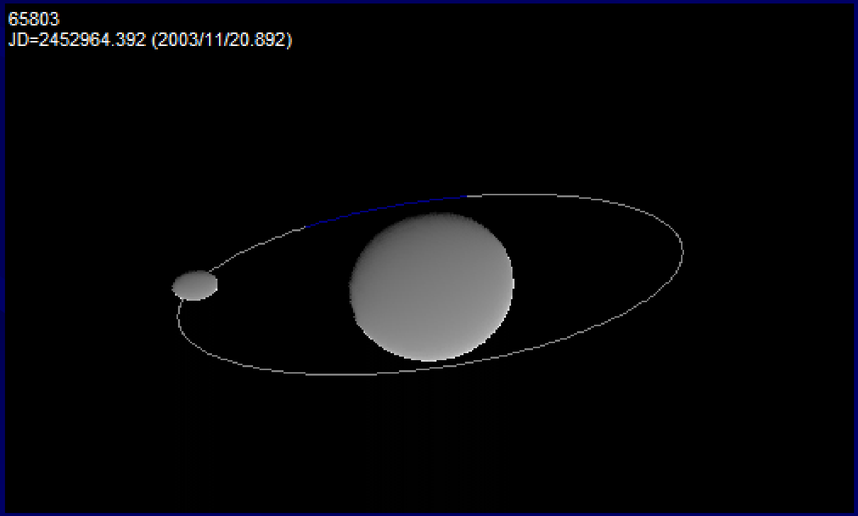
Preliminary orbital model – current assumptions

Circular orbit (note $e \leq 0.03$ found earlier to be 3-σ upper limit), zero inclination to the primary's equator.

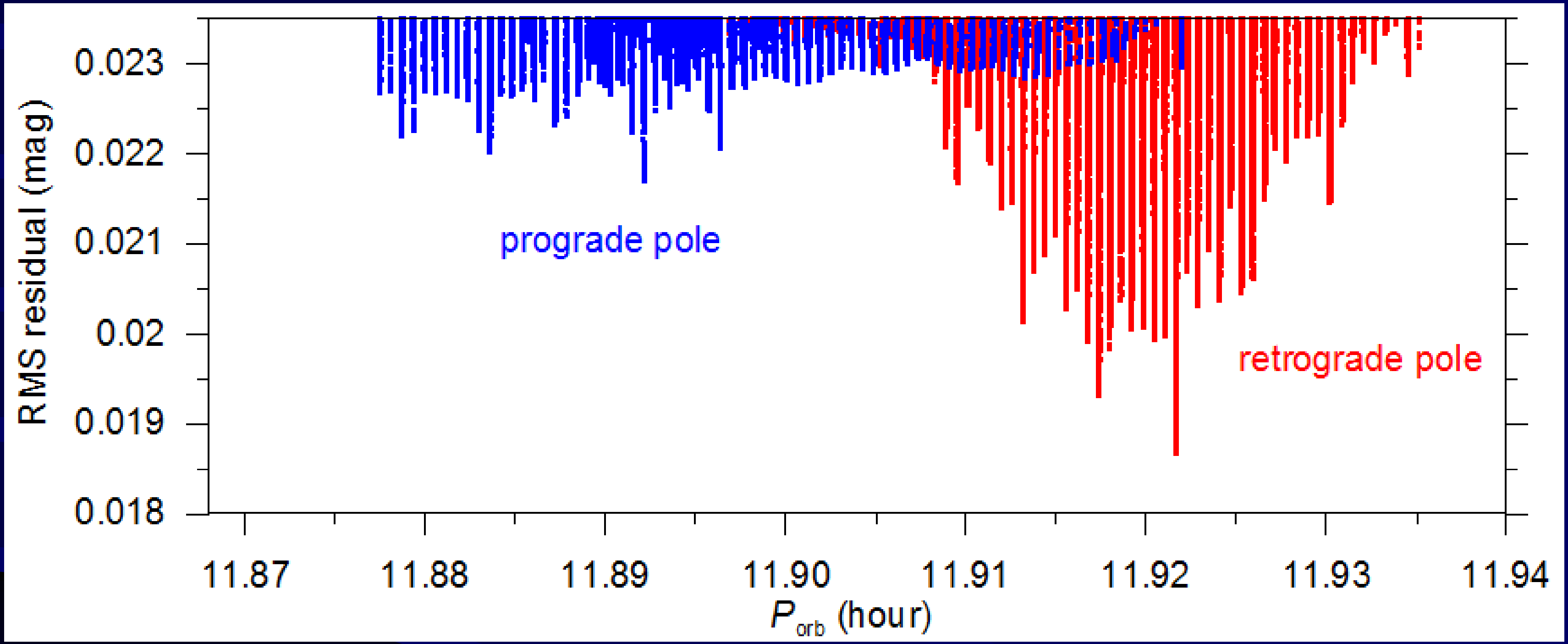
Orbital period constant. (Zero orbital drift by BYORP assumed. We expect to derive or constrain it in 2021.)

Primary modeled as a rotational ellipsoid (limb irregularities rotationally averaged) with $b_P/c_P = 1.1$

Secondary modeled as a triaxial ellipsoid with $a_S/b_S = 1.3$ and $b_S/c_S = 1.2$ in synchronous rotation (no libration)



Preliminary orbital model - P_{orb}



Prograde orbital pole ruled out. It's the retrograde orbital pole.

P_{orb} = 11.92164 ± 0.00003 h

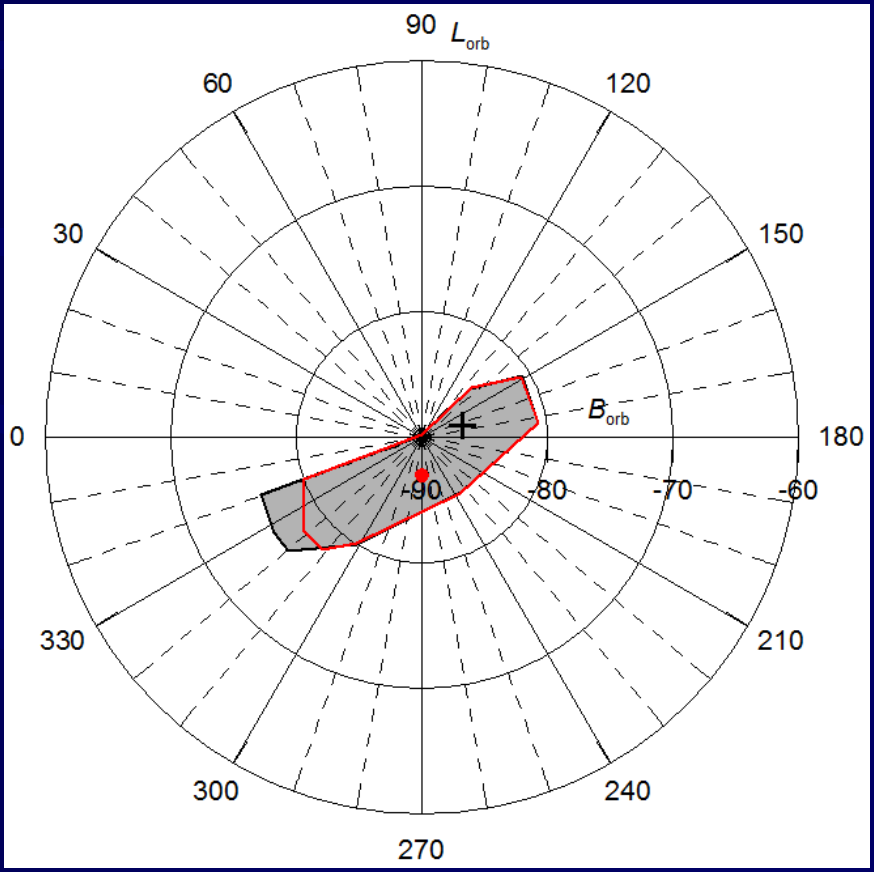
Other periods are possible if there is a non-zero orbital drift by BYORP.

Preliminary orbital model – pole direction

The allowed (3-σ) area constrained only a little more than we had before. (It's due to the given viewing and illumination geometry of the system on the observed dates.)

The nominal pole is L_{orb}, B_{orb} = 270º, -87º

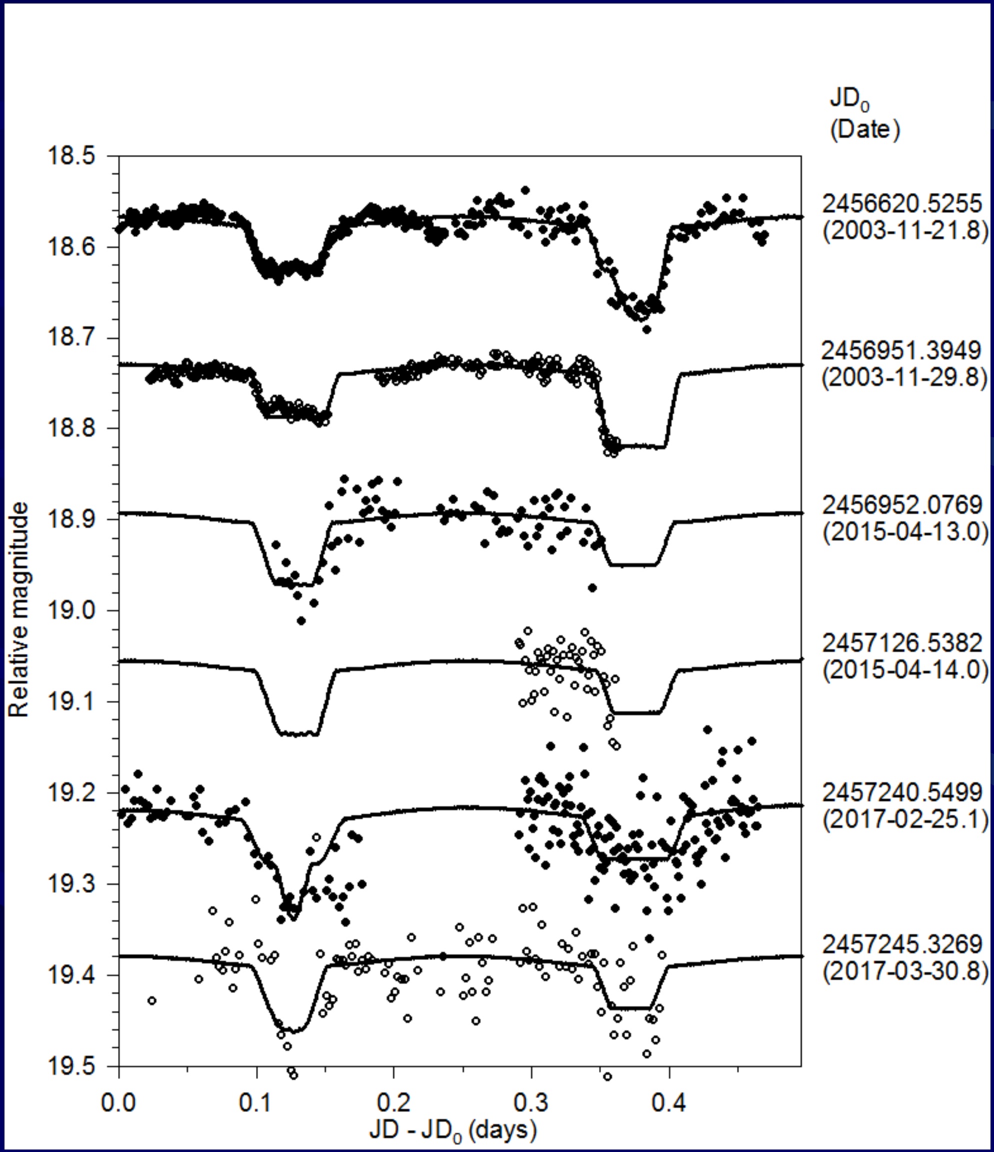
Sensitive to the assumptions of ellipsoidal shapes and zero inclination



Grey area – the previous pole solution (2003+2015 data)
Red outline – currently constrained pole area (+2017 data)

Preliminary orbital model – fit to the data

Nominal solution model (black curve) fit to a sample of the data.



Our goals for the 2017 apparition

How were they fulfilled?

Objectives for the 2017 observations

We planned:

1. Confirmation of the Orbital Pole 2
2. Gathering data for a future determination of orbit change by BYORP
3. Establishing a synchronous secondary rotation and a_S/b_S
4. Constraining inclination of the mutual orbit

We obtained:

1. Yes. The Orbital Pole 2 (Retrograde) was confirmed.

2. Yes. We expect to detect or constrain a drift of the Didymoon's orbit by BYORP in 2021.

3. No. A high quality data with errors ≤ 0.01 mag was not obtained. Will require at least one, possibly two high-quality nights at an 8-10m telescope around 2019 March 10 (V = 19.9, Dec = +9º); the 10.4-m GTC or Keck telescope would seem ideal.

4. No. The 2-month long observational interval was not enough to detect deviations in the event shapes due to a possible nodal precession of the Didymoon's orbit. We may try to cover a 3 and half month long interval from the beginning of January to mid-April 2019 (V ≤ 21.1).

Hints for observations in 2019

It would be good to cover the longer interval from the beginning of January to mid-April 2019. This will require large (6-10 m) telescopes in January and April when Didymos will be at *V* ~ 21.0 to get errors of 0.02 mag. Such long arc data would provide

- a constraint on inclination of the Didymoon's orbit
- more constraint on the orbital pole

It would be good to take one, better two nights with a large (8-10 m) telescope in the northern hemisphere around 2019 March 10 to get data with errors ≤ 0.01 mag. An ideal choice would seem to be the 10.4-m GTC or the Keck telescope. These observations should establish (confirm the assumed)

- synchronous secondary rotation and estimate a_S/b_S

Observations with medium size telescopes (~ 4 m) would be useful for monitoring the mutual events (to continue gathering data for detection/constraint of an orbital drift by BYORP in 2021).

Thank you

Additional or older slides

Observations in 2017

<u>The next favorable apparition</u>: 2017 Janua
Didymos will be brightest with V = 20.3 ar
on 2017-03-28.

Our objectives:

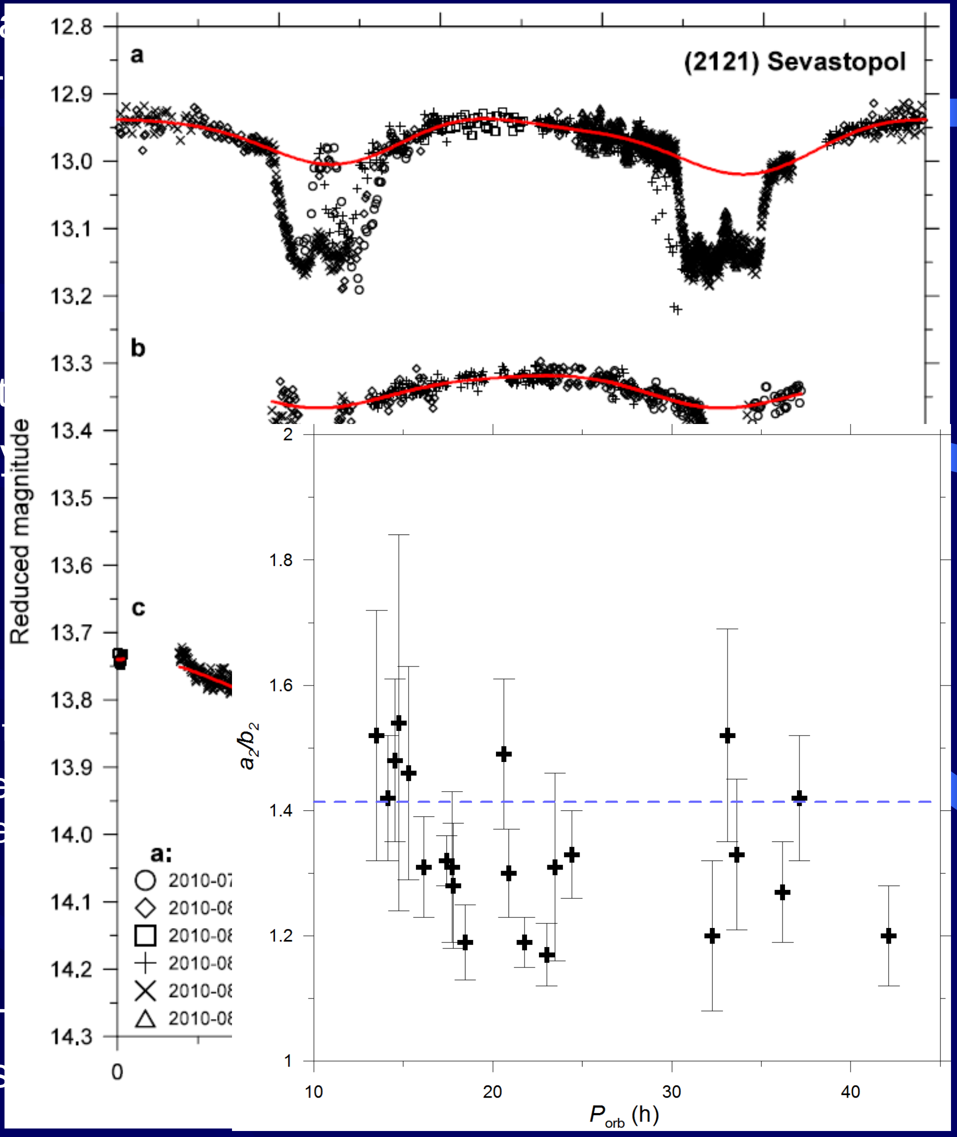
1. Confirmation of the Orbital Pole 2
2. Gathering data for a future determinat
3. Establishing a synchronous secondar
4. Constraining inclination of the mutual

Notes:

Re. 2. The predicted ΔM_d = 2.5° yr^{-2} (using the
be detected by 2022, if it is not in equilibrium wi

Re. 4. If $i \neq 0$, the nodal precession could be de
estimate dΩ/dt = -1.7 ± 0.5 °/day, i.e., Ω change

We have already submitted proposals for
ESO NTT 3.5-m, the GTC 10-m and the H
More observations (with ≥ 4 m telescopes
goals.



Observations in 2018-2021

Further apparitions:

2018 December to 2019 May (opposition on 2019-03-13, V = 19.8)

2020 April to 2021 May (opposition on 2021-02-20, V = 18.9)

Objectives:

1. Refining the Didymos B’s ephemeris to constrain targeting of the DART impact
2. Determination of orbit change by BYORP

+ completing goals from the 2017 campaign that will not be reached yet.

Notes:

- With the 18-year Didymos dataset covering 2003-2021, we estimate that we will have the Didymos B's ephemeris good to ± 8° (3-σ uncertainty) in true anomaly for the epoch in October 2022 (i.e., at the time of the DART impact).
- An orbital drift caused by BYORP may be detected (or constrained, if Didymoon is in a BYORP-tides equilibrium) in 2021 already, but a confirmation and refinement in 2022 will be needed.

As Didymos will be relatively bright around the 2019 and 2021 oppositions, relatively small telescopes of the 1.5-3m class will produce good data.

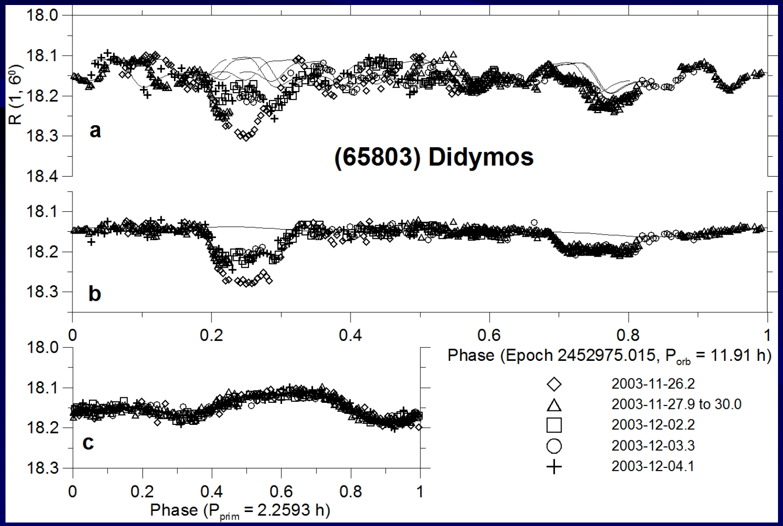
(65803) Didymos – discovery observations

The asteroid was discovered by *Spacewatch* from Kitt Peak on 1996 April 11. Designated 1996 GT.

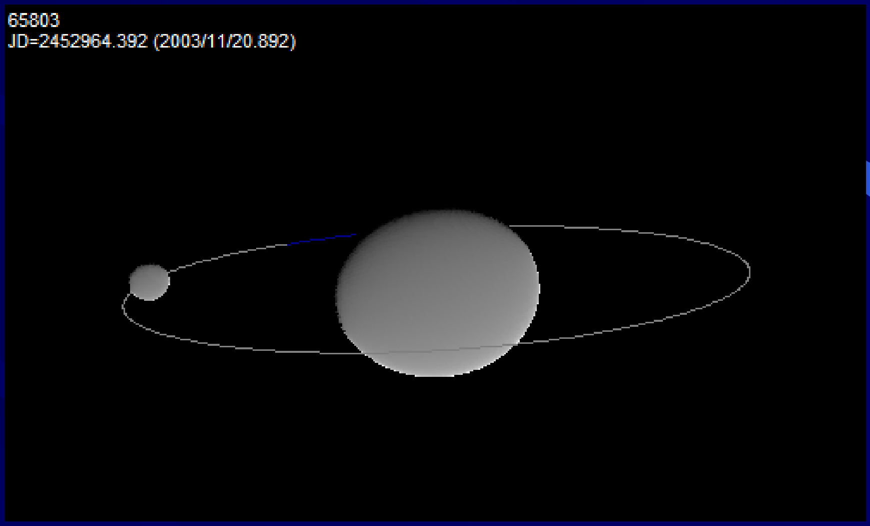
Its binary nature was revealed by both photometric and radar observations obtained around its close approach to Earth (min. distance 0.05 AU) during 2003 November 20-24.

The photometric observations were taken by P. Pravec and P. Kušnirák from Ondřejov Observatory, by D. Pray from Carbuncle Hill Observatory, and by A. Grauer and S. Larson from Steward Observatory. The radar observations were taken by L.A.M. Benner, M.C. Nolan, J.D. Giorgini, R.F. Jurgens, S.J. Ostro, J.-L. Margot and C. Magri from Goldstone and Arecibo. *(Pravec et al. 2003)*

Mutual events (eclipses+occultations) between the binary system components observed in 2003 (a sample of the data is shown) and a model of the system:



(Pravec et al. 2006)



(Scheirich and Pravec 2009)

Additional observations of Didymos in 2015

2003-11-20 to 12-20

Favorable observing conditions around and after close approach to Earth

V = 12.8-15.0, distance 0.05-0.16 a.u.

16 nightly runs

Telescopes: 0.65, 0.5, 0.35 m

Rms error:

0.008 mag (11-20 to 12-04), *V* = 12.8-13.3

0.012 mag (12-16 to 12-20), *V* = 14.7-15.0

2015-04-13 to 14

Observed at a large distance, near the aphelion of its heliocentric orbit

V = 20.5-20.6, distance 1.25 a.u.

1 full and one partial nightly run (duration 5.7 and 1.7 h)

Telescope: 4.3 m

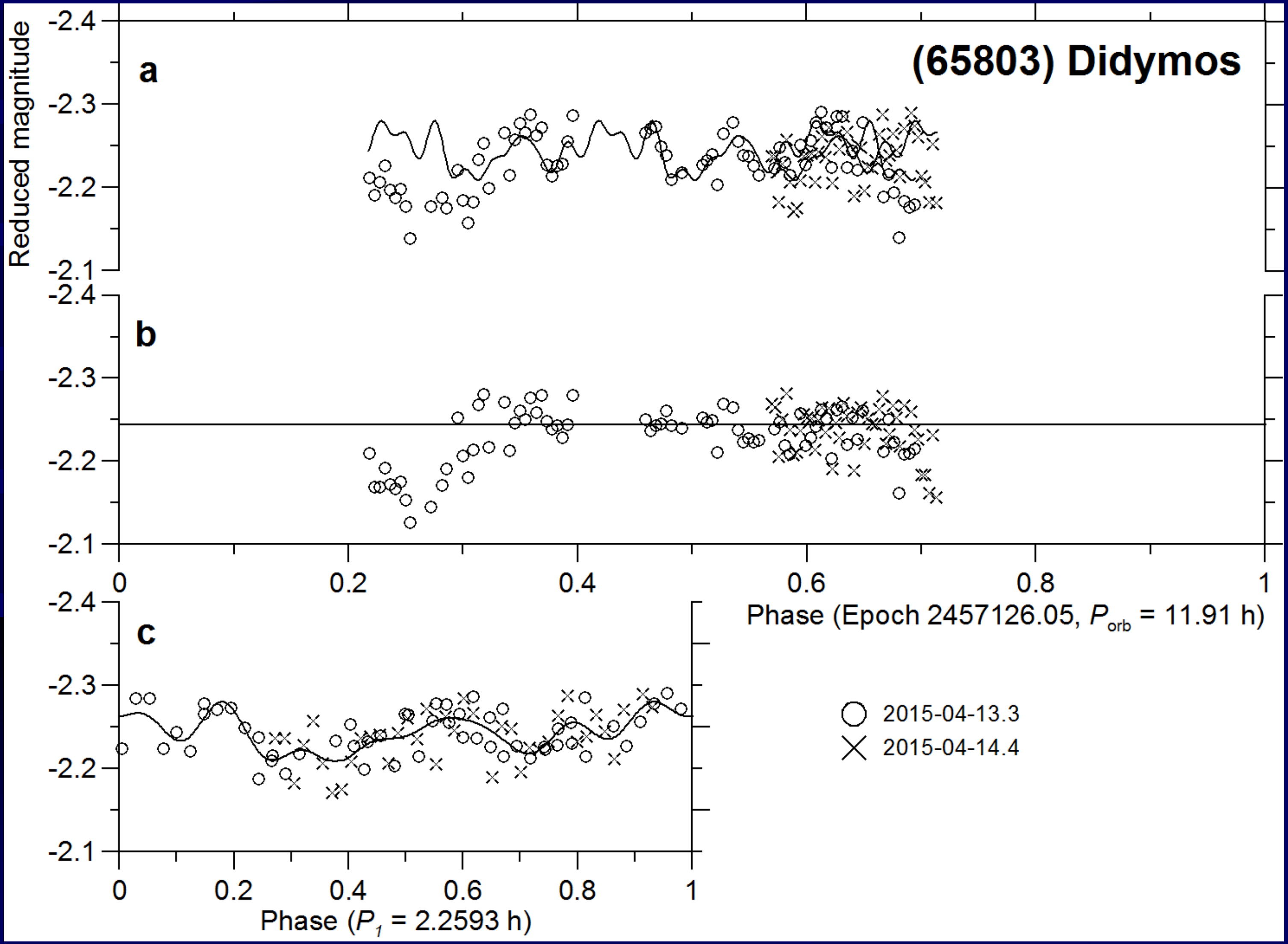
Rms error:

0.024 mag

Observers: N. Moskovitz, A. Thirouin

(A number of unsuccessfull attempts with smaller telescopes or in sub-optimal sky conditions.)

2015 data



(65803) Didymos
a
b
c
Reduced magnitude
-2.4
-2.3
-2.2
-2.1
0
0.2
0.4
0.6
0.8
1
Phase (Epoch 2457126.05, P_{orb} = 11.91 h)
Phase (P_1 = 2.2593 h)
2015-04-13.3
2015-04-14.4

Didymos orbital model

Didymos orbital model (1)

We modeled the observed mutual events of Didymos using the method of Scheirich and Pravec (2009). We solve for a precessing Keplerian orbit of the secondary.

Following function is minimized:

$$\mathrm{RMS}(L_{\mathrm{orb}}, B_{\mathrm{orb}}, P_{\mathrm{orb}}, a/D_P, D_S/D_P, L_0, e, \omega, \mathrm{shapes}) = \sqrt{\frac{\sum(o_i - c_i)^2}{N}}$$

Shapes of the components are approximated with ellipsoids if only lightcurve data are available, or a shape model (e.g., from radar observations) is used.

<u>Main assumptions:</u>
Same albedo of both components
Uniform surface light scattering properties
i = 0 (i.e., there is not present a nodal precession of the mutual orbit)

Note: Error budget predominated by systematic model errors, not statistical (random) errors.
Realistic uncertainties of the parameters are substantially greater than formal chi^2-errors.
We estimate realistic conservative ("3-σ") errors by a visual inspection of the sensitivity of the fitted model to individual parameters.

Didymos orbital model (2)

Main parameters:

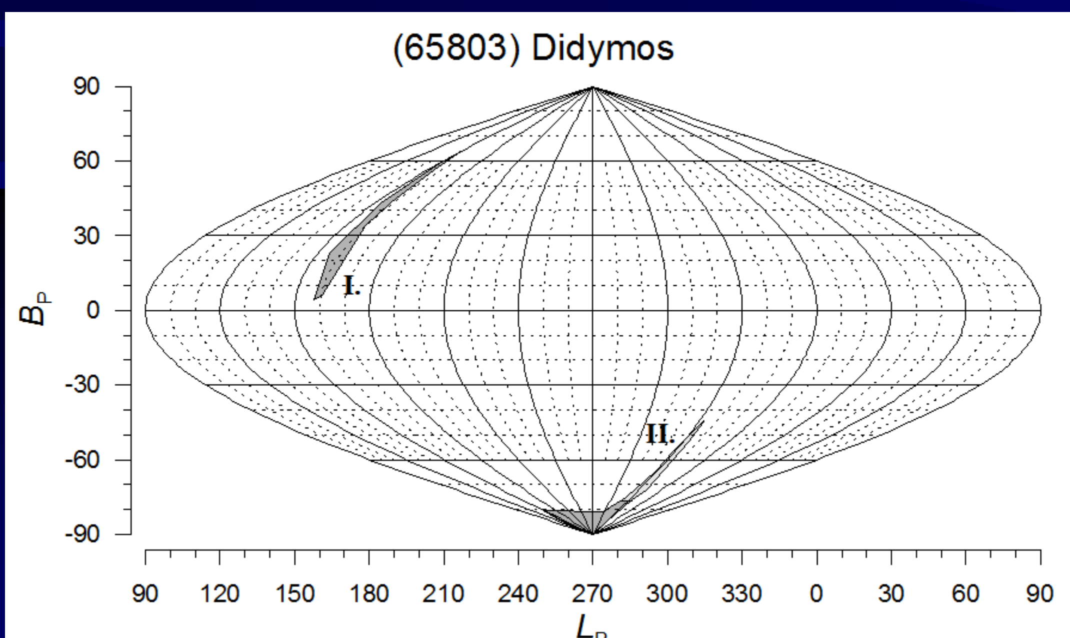
<u>Diameter ratio</u>: $D_S/D_P = 0.21 \pm 0.01$ Photometry *(Scheirich and Pravec 2009)*

<u>Orbital period</u>: $P_{orb} = 11.920\ +0.004/-0.006$ h Photometry *(Scheirich and Pravec 2009)*

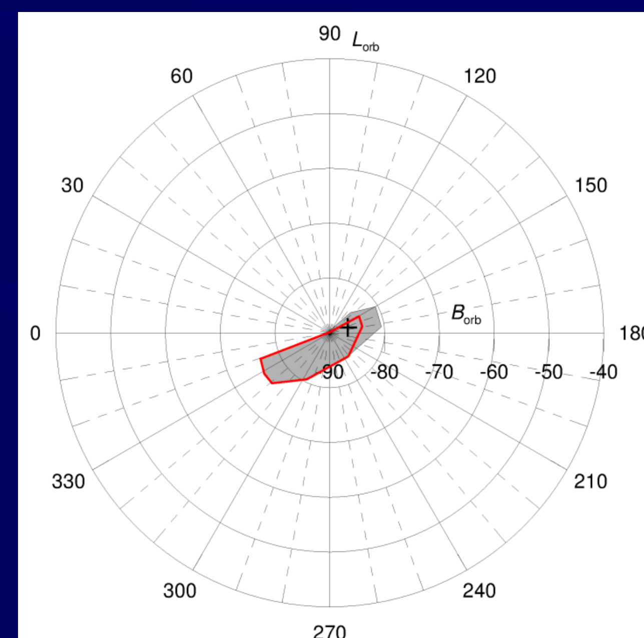
<u>Eccentricity</u>: $e \leq 0.03$ Photometry *(Scheirich and Pravec 2009)*

<u>Orbital pole</u>: $L_{orb}, B_{orb} = 310°, -84°$ Photometry *(Scheirich and Pravec 2009, updated)*

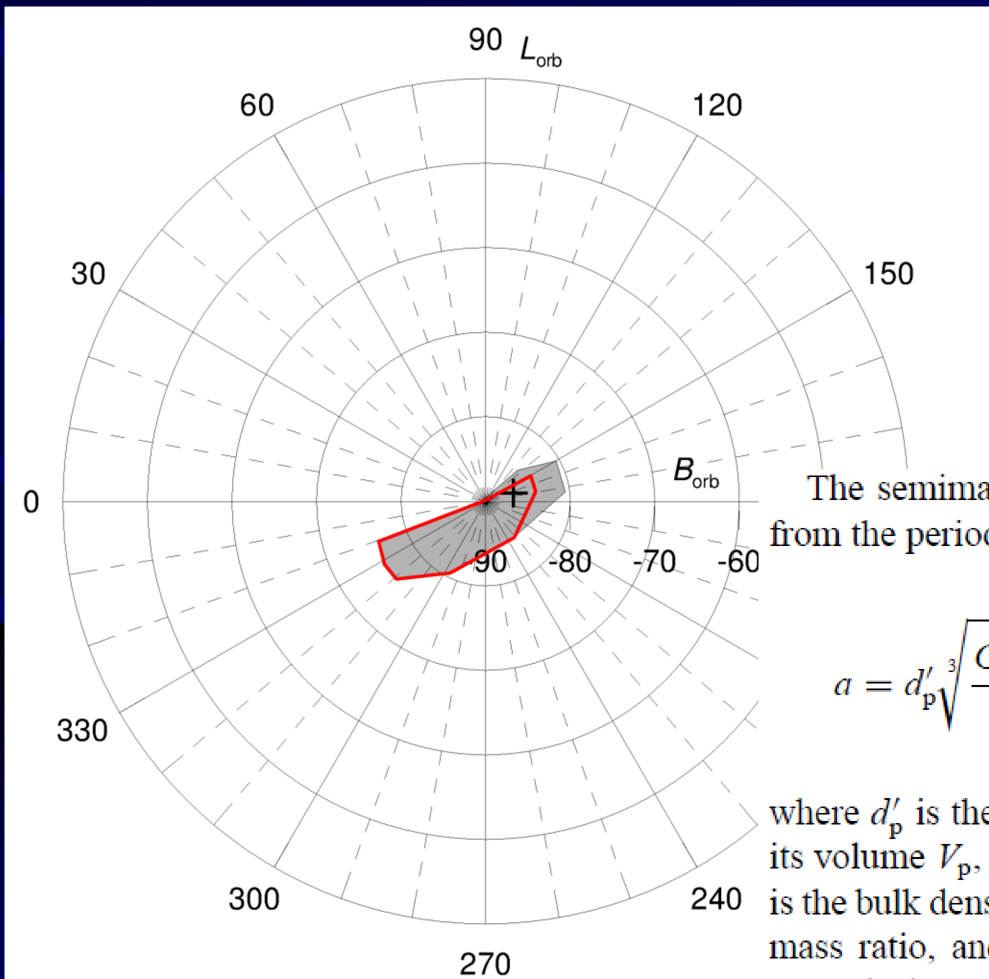
Allowed (conservative 3-σ uncertainty) orbital pole areas for the two solutions by Scheirich and Pravec (2009) from the 2003 data:



The 2015-04-13 data rules out Solution 1 and it constraints the Solution 2 to latitude $B_{orb} < -76°$:



Didymos orbital model (3)



With the 2015-04-13 data, the orbital pole latitude is constrained to B_{orb} < -76°.
With the preliminary radar shape model for the primary, the area is further constrained (the red curve).

Constraint on primary <u>bulk density</u>:

The semimajor axis a of the mutual orbit can be estimated from the period P_2 using Kepler's third law in the form

$$a = d'_p \sqrt[3]{\frac{G\rho(1+q)P_{orb}^2}{24\pi}} = 0.225 d'_p \sqrt[3]{\rho(1+q)P_{orb}^2}, \qquad (2)$$

where d'_p is the mean diameter of the primary that is related to its volume V_p, $d'_p = \sqrt[3]{6V_p/\pi}$, G is the gravitational constant, ρ is the bulk density of the primary, q is the secondary-to-primary mass ratio, and P_{orb} is the orbital period of the system. The numerical constant 0.225 is computed for P_{orb} in hours and ρ in g/cm^3. An upper limit for the bulk density of the 1996 FG_3

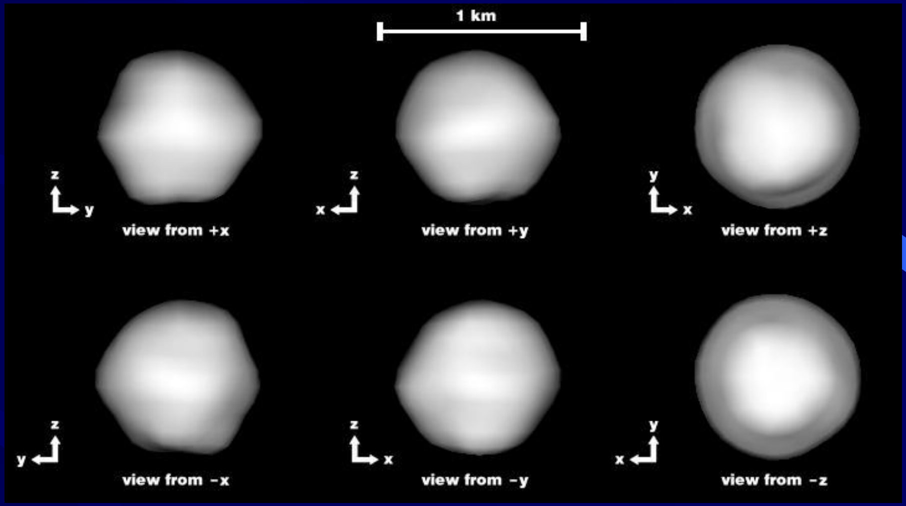
Allowed (conservative 3-σ uncertainty) ar

Observations in next apparitions

Didymos components – sizes and shapes

<u>Mean</u> (volume-equivalent) <u>primary diameter</u>:	D_P = 0.75 km (unc. 10%)	Radar
<u>Secondary-to-primary mean diameter ratio</u>:	D_S/D_P = 0.21 ± 0.01	Photometry
<u>Mean</u> (volume-equivalent) <u>secondary diameter</u>:	D_S = 0.157 ± 0.018 km	from above

<u>Primary shape</u>:
Unelongated, not differing much from a spheroid.
Primary equatorial axes ratio $a_P/b_P < 1.1$ — Photometry
Primary polar axis not well constrained,
but probably not much flattened.



Low-resolution primary shape model from combined radar+photometry data, (L_P, B_P) = (313, -79)
Courtesy of L. Benner.

<u>Secondary shape</u>:
Observationally unconstrained yet. Assumed a_S/b_S = 1.3 ± 0.2 and b_S/c_S = 1.2 ± 0.2 based on data for the secondaries of other asteroid binary systems.

Didymos primary – other properties

Rotational period: $P_P = 2.2593 \pm 0.0008$ h — Photometry *(Pravec et al. 2006)*

Geometric albedo: $p_V = 0.16 \pm 0.04$ — Combined photometry and radar

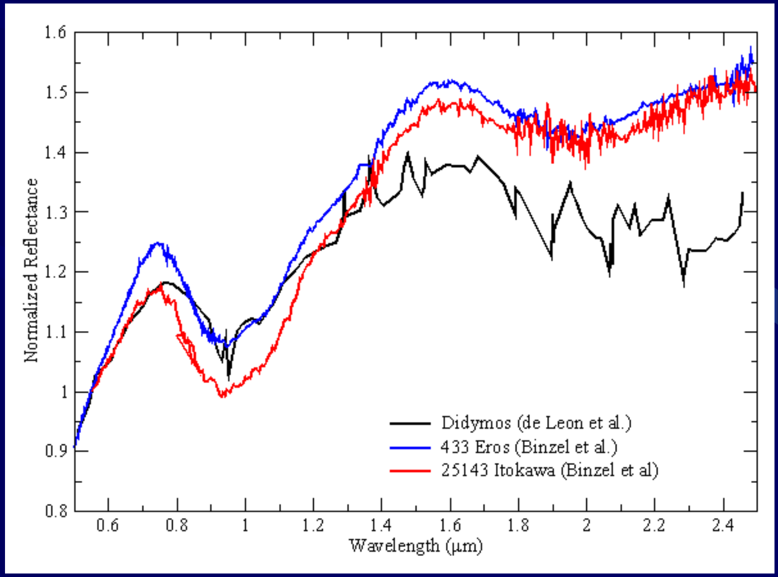
Mass: $M_P = (5.22 \pm 0.54) \cdot 10^{11}$ kg — Radar *(Fang and Margot 2012)*

Bulk density: $\rho_P \sim 2400\text{-}2600$ kg m^{-3} (unc. 30%) — Radar, Photometry

Taxonomic class: S — Spectrum (de León et al. 2010)

The internal structure of Didymos primary is thought to be rubble pile. No cohesion between "particles" (building blocks) is required for its stability, unless there are high slopes on the surface. There is probably a significant macro-porosity of the primary's interior on an order of a few ten percent.

The spin rate is probably close to critical; the gravitational acceleration at and around the equator may be very low with the centrifugal force of nearly the same magnitude as the gravity.



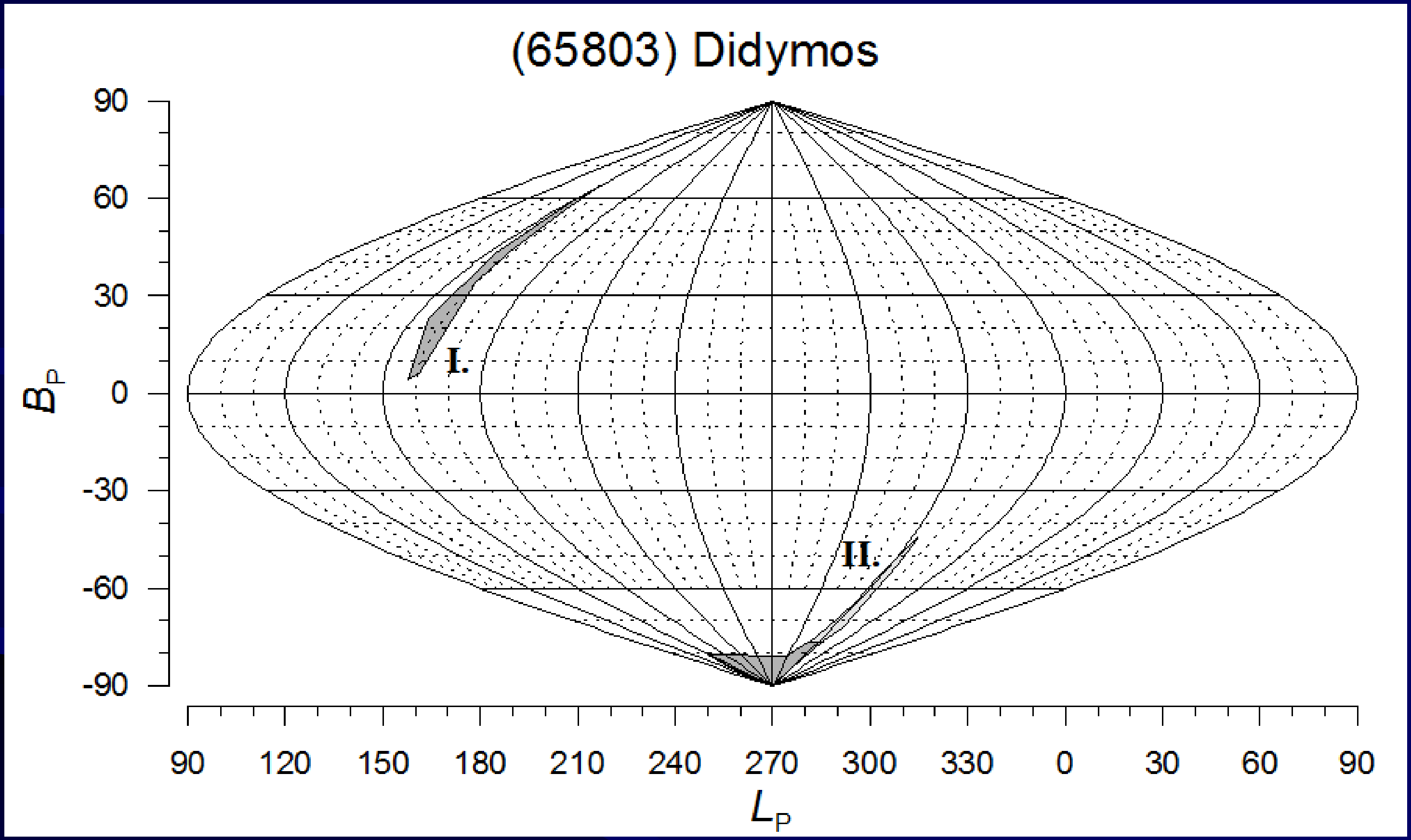
Didymos in context of the binary asteroid population

Didymos appears to be a typical member of the population of small binary asteroids formed by spin-up fission, in most of its characteristics.

With P_P = 2.26 h and P_{orb} = 11.9 h, it lies close to the high end of the distributions of primary rotational and secondary orbital rates among small binary asteroid systems – this might be due to its bulk density higher than average for binary asteroids.

Thank you!

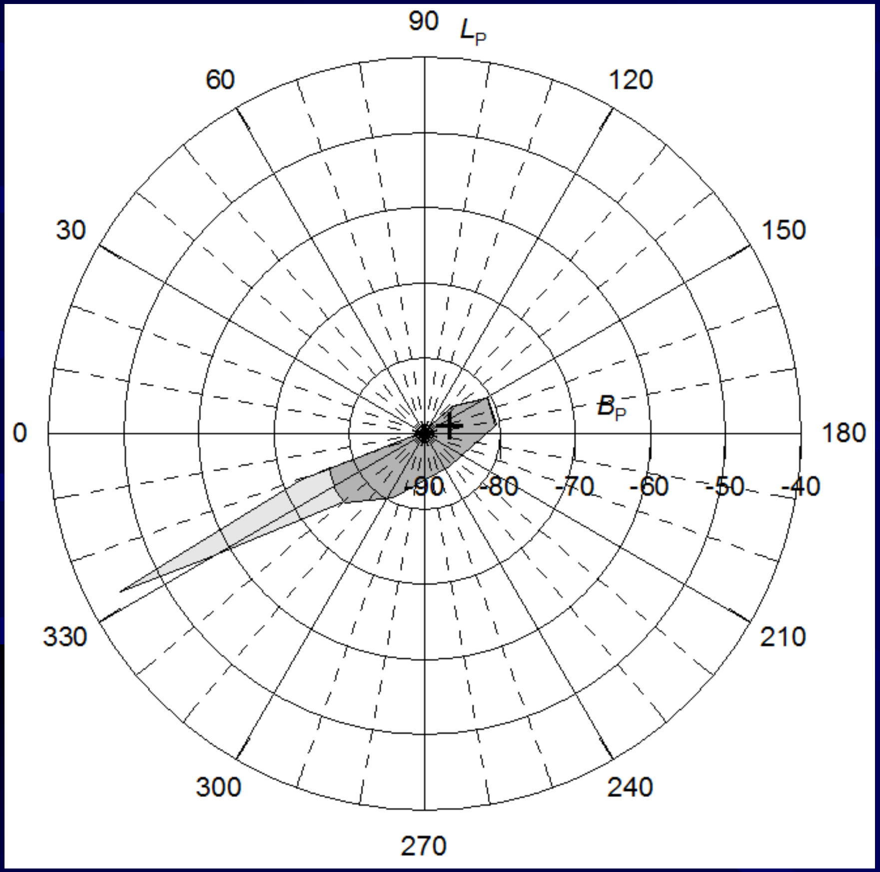
Didymos orbital pole



Scheirich and Pravec (2009), updated

The attenuation (assumed eclipse/occultation event) observed on 2015-04-13 rules out Pole Area 1 and it constrains Pole Area 2 substantially.

Didymos orbital pole (cont.)



3-σ uncertainty area plotted

With the 2015-04-13 data, the orbital pole latitude is constrained to $B_P < -76°$

Updated constraint on bulk density:
Formal best fit for density 2.6 g/cm^3
3-σ lower limit: 1.8 g/cm^3
3-σ upper limit: > 3 g/cm^3
The primary bulk density is not well determined because of poorly constrained primary polar flattening and a/D_1 – a shape model from the radar observations would help tremendously.

Observations in 2017

<u>The next favorable apparition</u>: 2017 January to May

Our objectives:

1. Confirmation of the Orbital Pole 2
2. Gathering data for a future determination of orbit change by BYORP
3. Establishing a synchronous secondary rotation

Objective 1. <u>Confirmation of the Orbital Pole 2</u>

Telescope time needed: One full night (a coverage of about 2/3 of P_{orb}, i.e., about 8 hours) at minimum, between 2017-03-21 and 04-03.

Telescope size needed: 4 m at minimum.

Justification: Didymos will be <u>brightest with V = 20.3 around 2017-03-28</u>. A scaling from the observations with the 4.3-m on 2015-04-13 gives, assuming the sky+background noise dominates, an expected rms error of 0.020 mag with the same telescope in the same sky conditions.

Observations in 2017 (cont.)

Objective 2. Gathering data for a future determination of orbit change by BYORP

Need to resolve primary vs secondary event with additional observations taken before 03-06 or after 04-19. Didymos will be *V* ~ 21.0, so a slightly larger telescope (5 m?) will be needed. One full and one partial night could suffice.

Objective 3. Establishing a synchronous secondary rotation

Observations with errors of 0.01 mag or lower could resolve a secondary rotational lightcurve (outside events). Two nights with a ~6 m or larger telescope between 2017-03-21 and 04-03 needed.

Questions/Issues:

- *What will be our priorities for the above objectives?*
- *Should we try to get telescope time on some 4+ m telescopes through the normal channels of TACs like we did in 2015, or could we arrange a more flexible use of some suitable telescope(s)?*