OSIRIS-REx
ASTEROID SAMPLE RETURN MISSION

Observations of Bennu's Increasing Rotation Rate, YORP, and Implications for Bennu's Evolution

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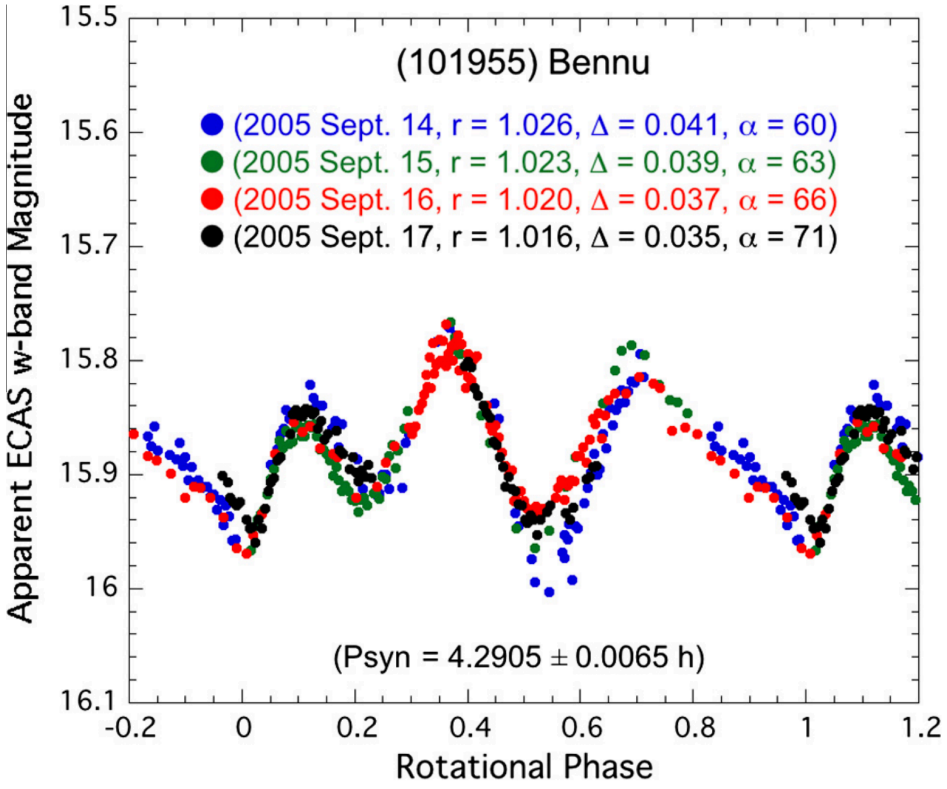
Rotation State of Bennu

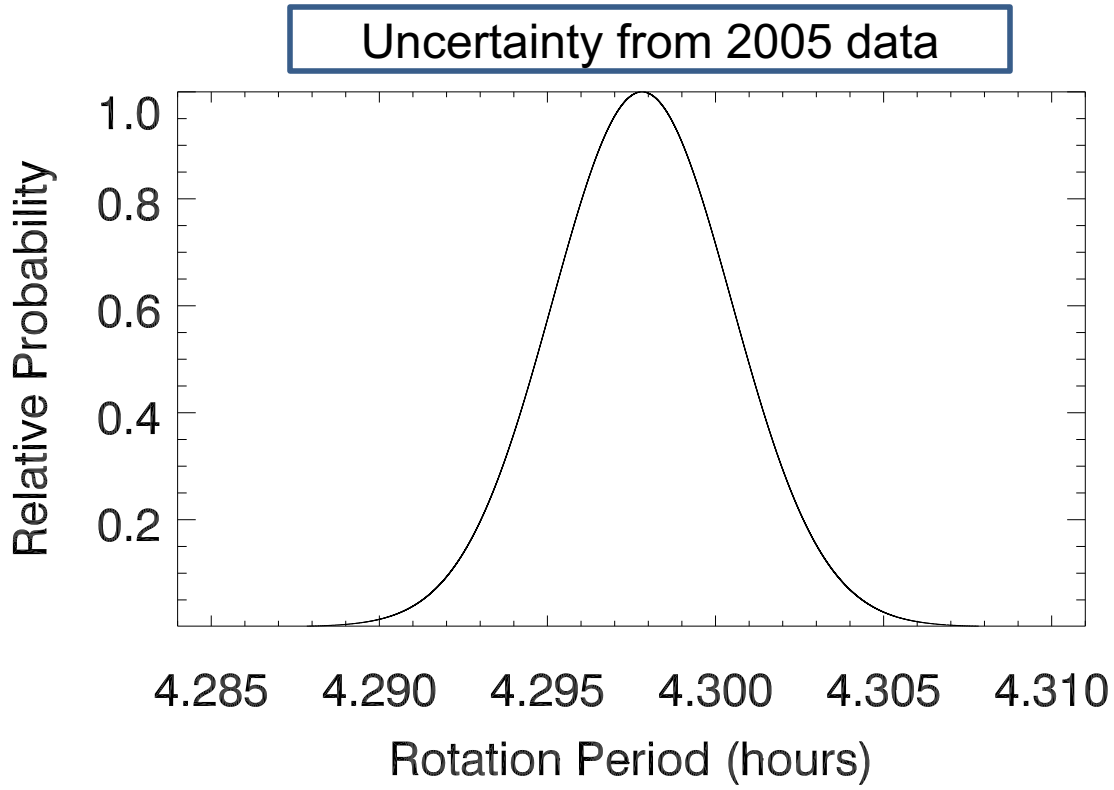
- Ground-based visible lightcurves of Bennu were obtained in 1999 and 2005, before Bennu (then 1999 RQ36) was a spacecraft target.
- As is common, lightcurves were taken for a few days each time, resulting in a rotation period accurate to about 0.1%: Fine for physical description, but not to maintain phase over apparitions.
- Bennu has a low-amplitude 3-peaked lightcurve consistent with its round shape.

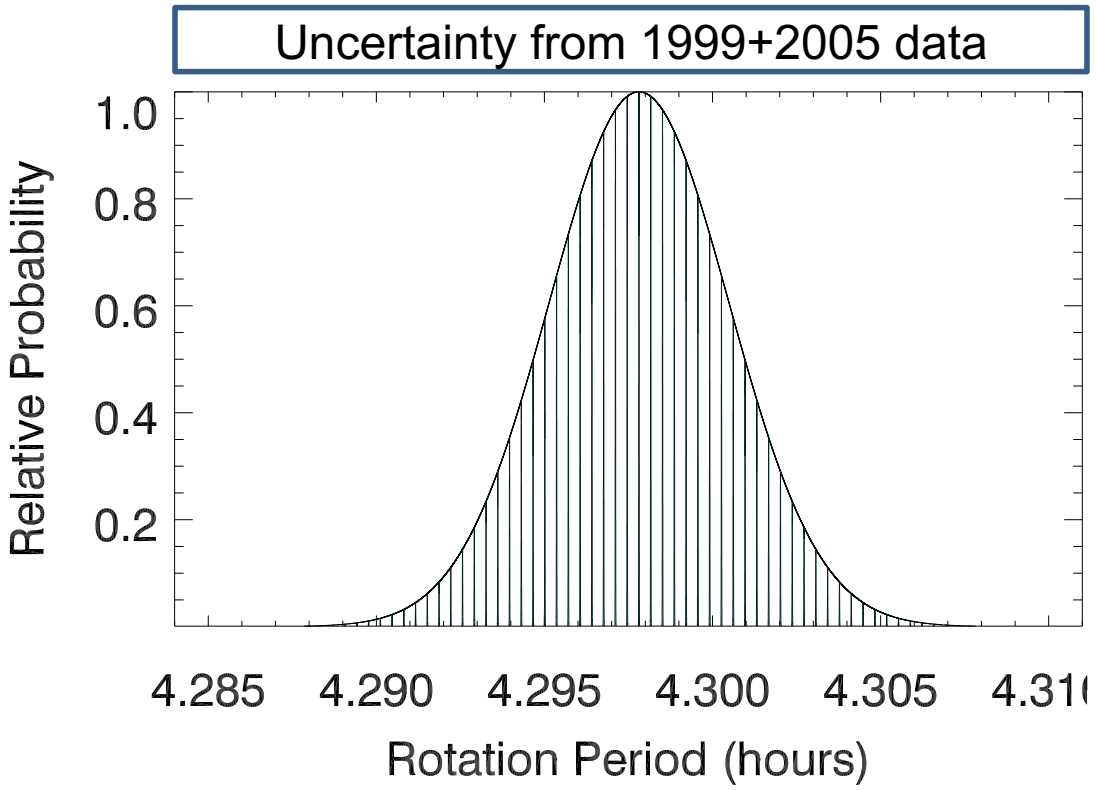


2005 lightcurve (Hergenrother et al 2013)

Rotation based on 1999 and 2005 data

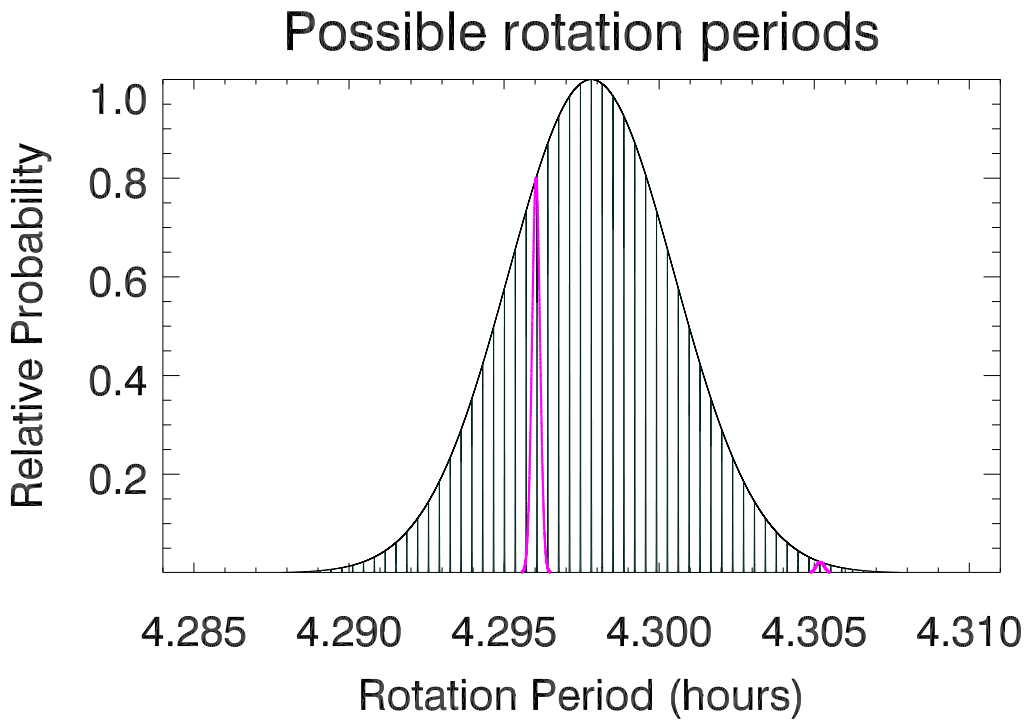
- Based on the 1999 and 2005 data, the rotation period was 4.297 h +/- 10 rotations /6 years (1-sigma).





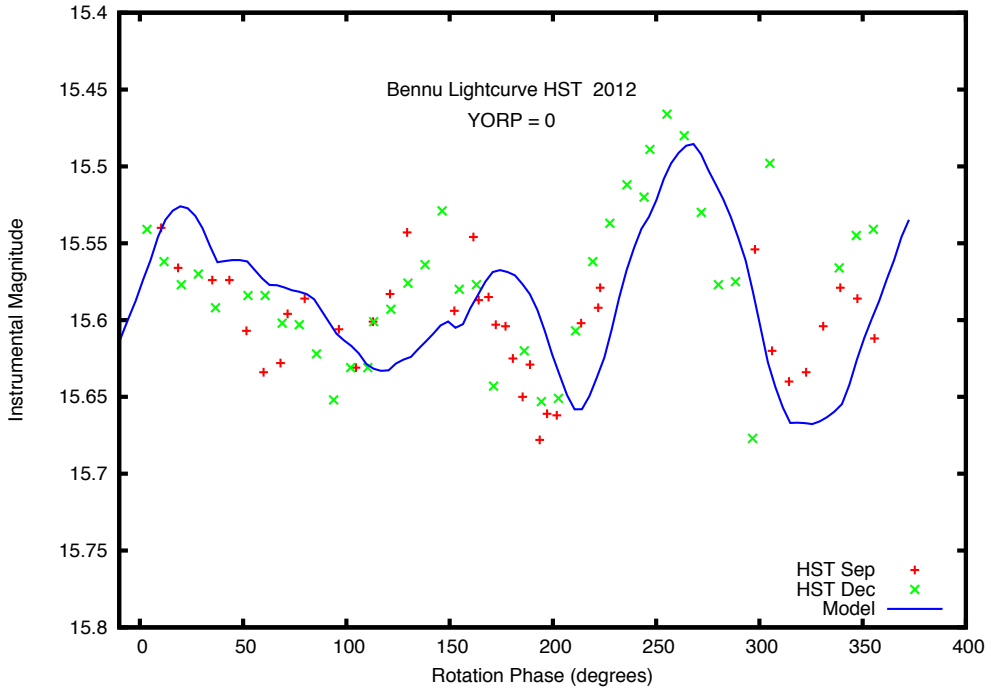
Added two epochs in 2012

- Ground-based campaign in 2011 unsuccessful.
- Two epochs of HST data ~ 3 months apart unambiguously determine period

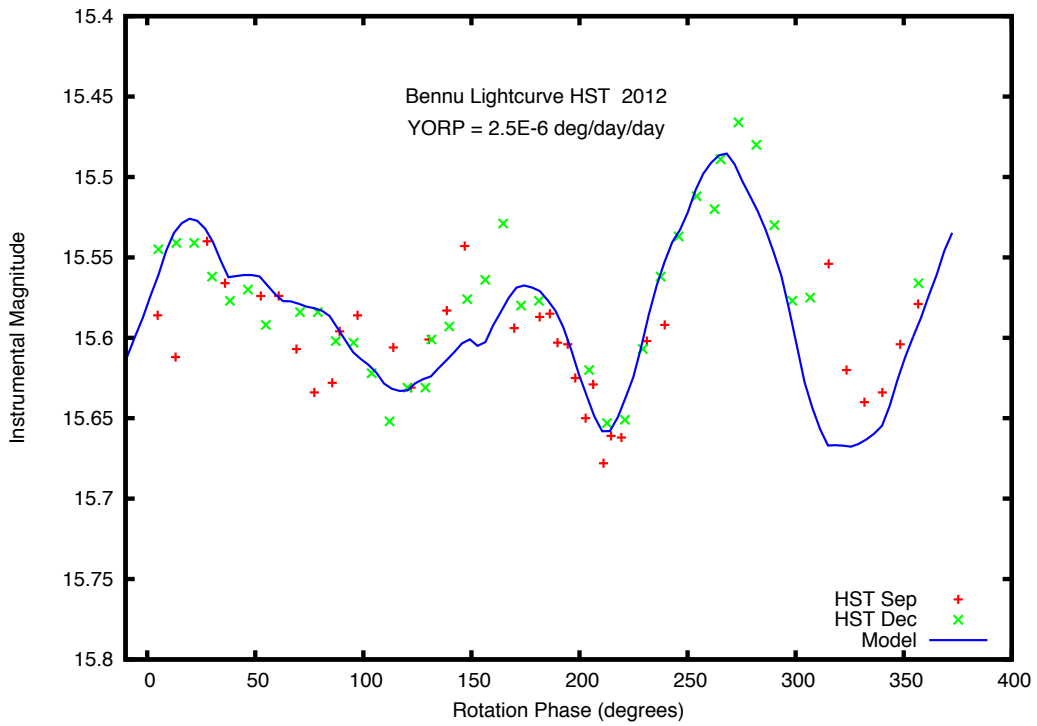


HST lightcurves compared to 2012 model with five extra rotations

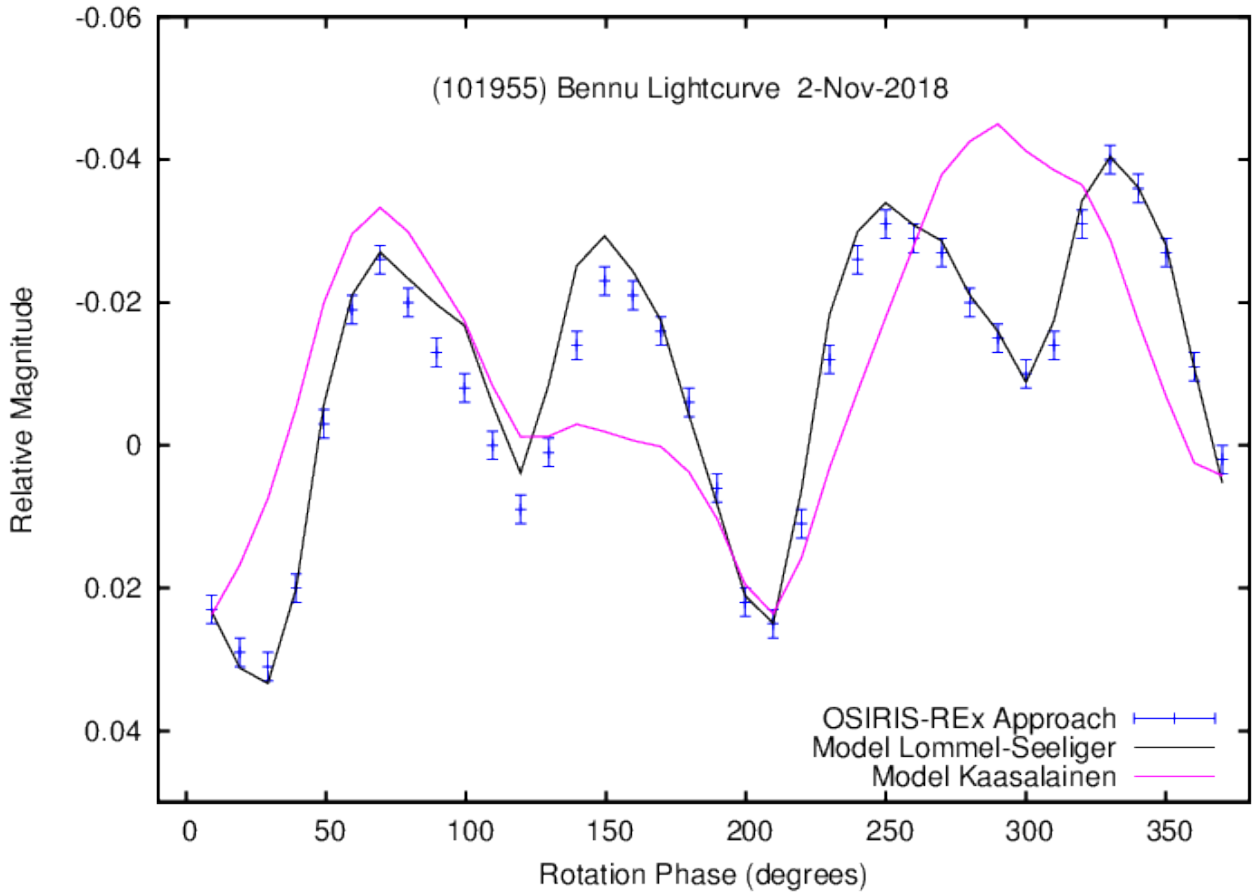
HST Data plotted against predicted lightcurve from radar shape model



Added small YORP acceleration

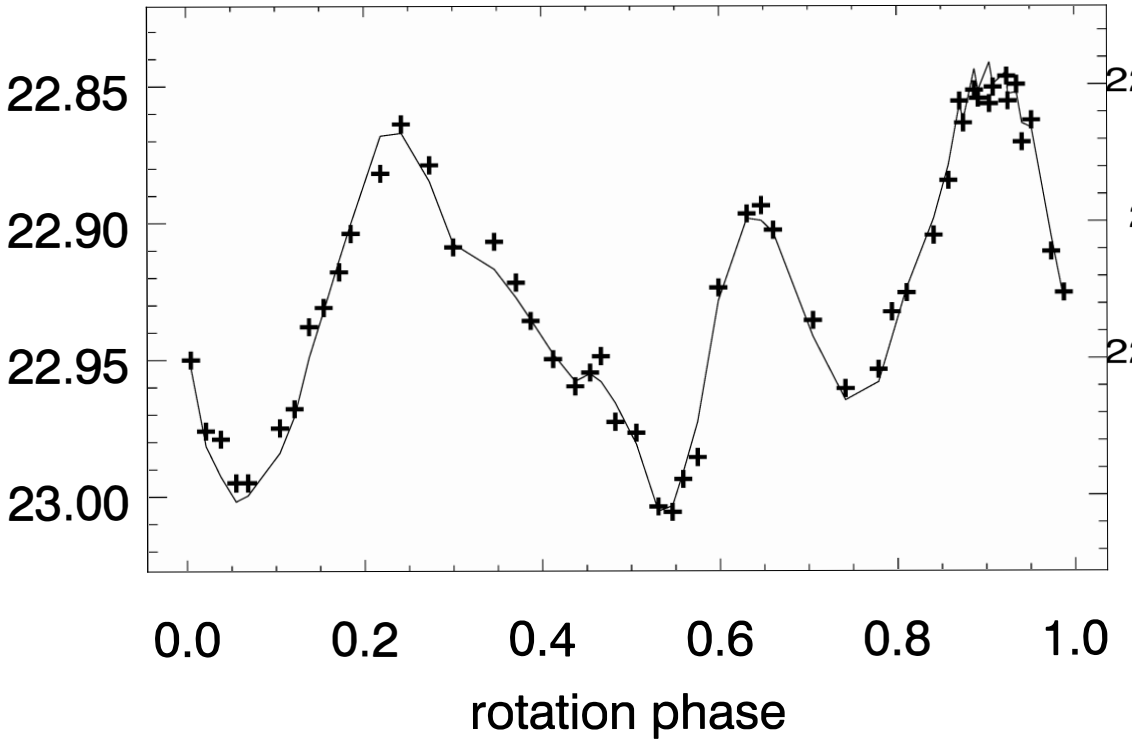


- As we approached Bennu, the lightcurve looked very different.
- Low phase angle (~ 10 degrees) and integrating resolved images.
- Scattering function is very important and not uniform
  - Adds uncertainty in comparing ground-based and proximity data.

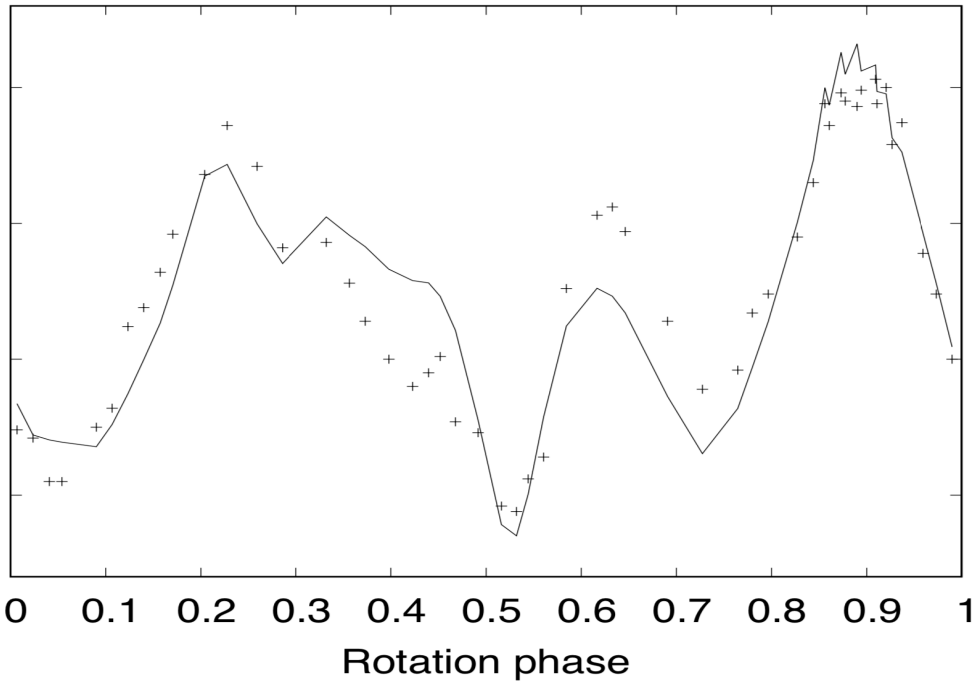


2005 Lightcurve

Radar Shape Model

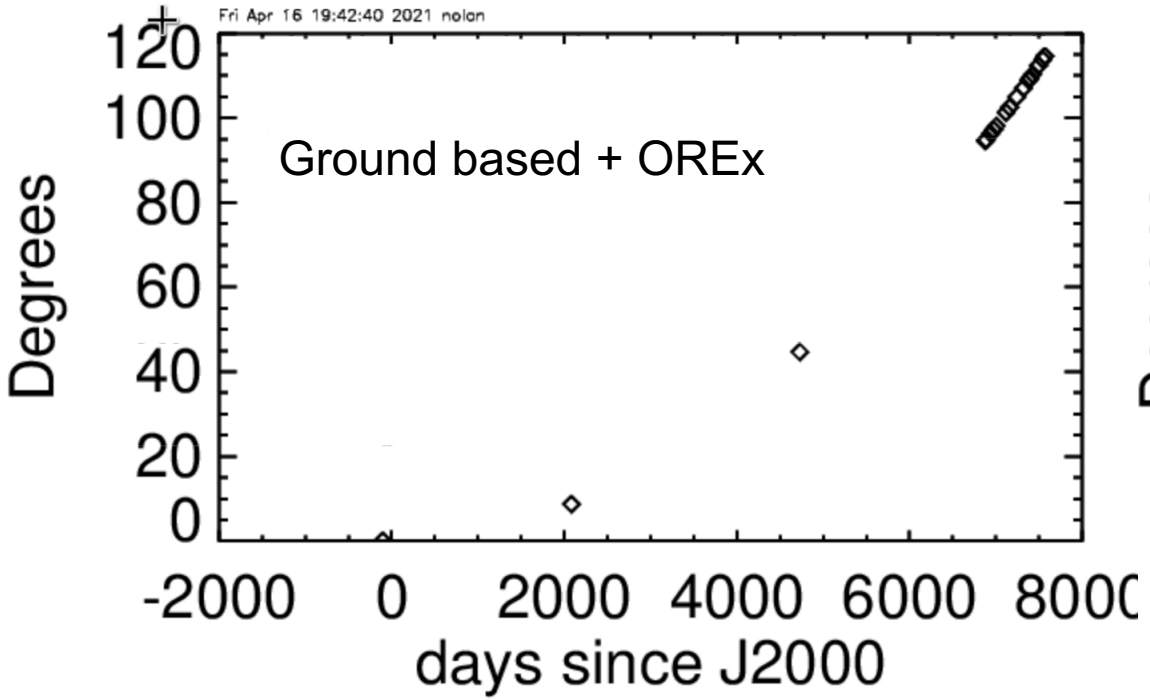


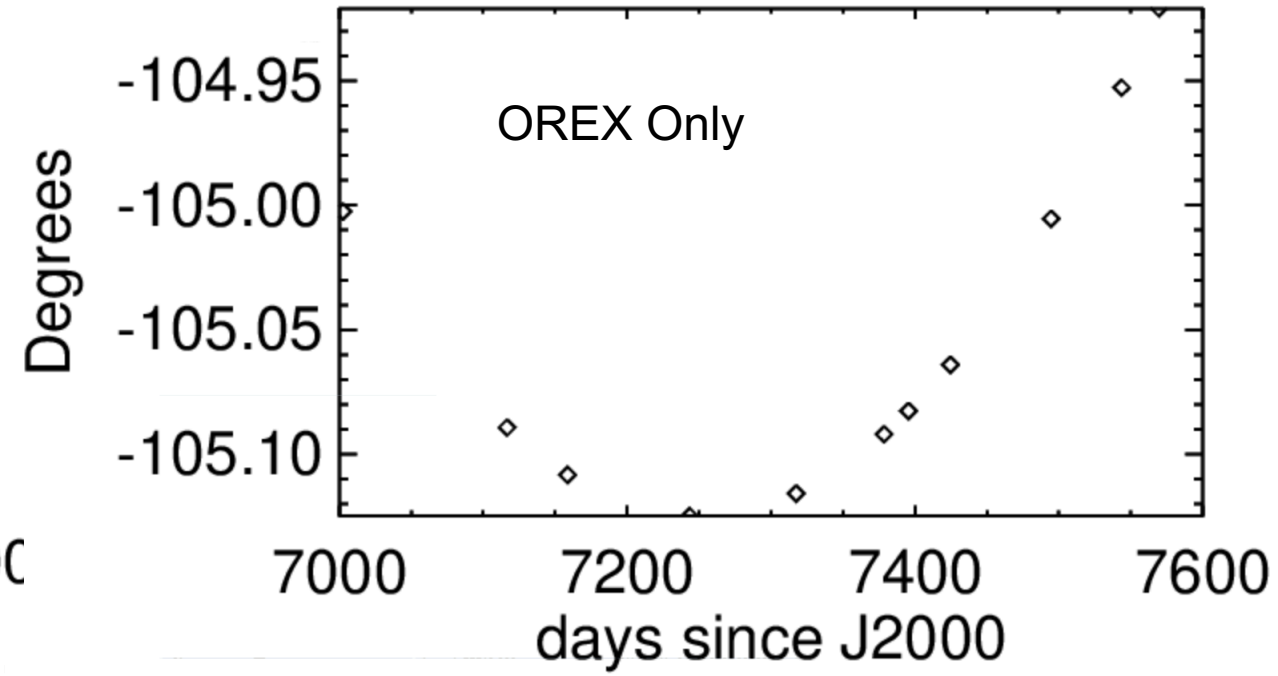
OSIRIS-REx Shape Model



Proximity Operations at Bennu

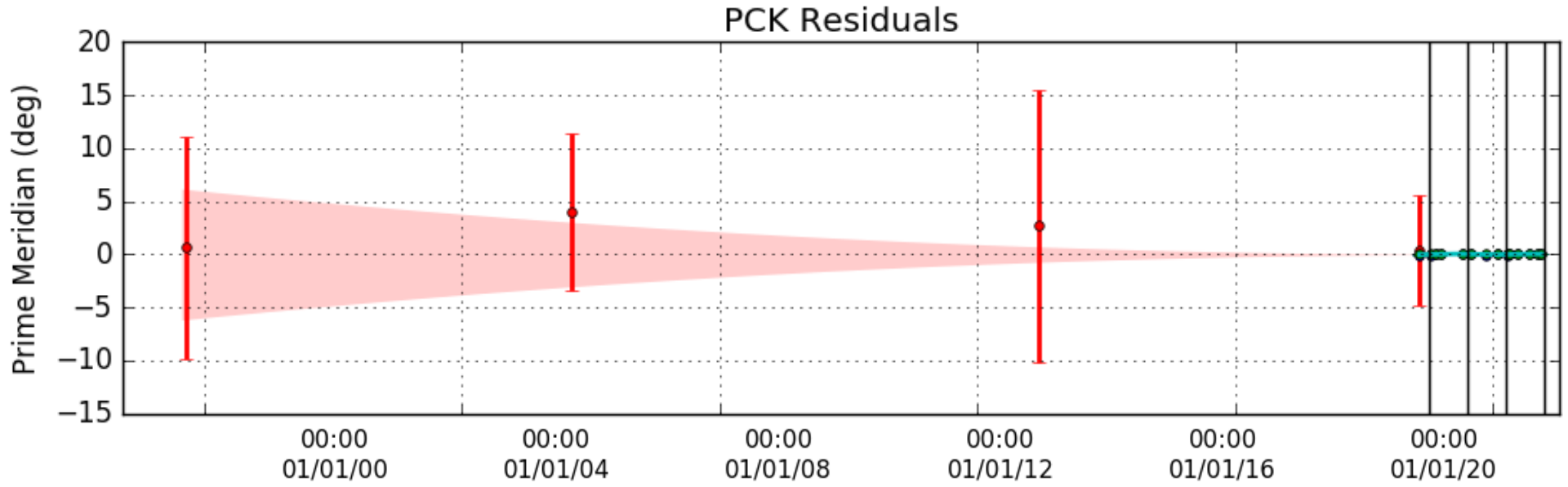
- The OSIRIS-REx Navigation team solves for the instantaneous rotation phase when solving for the spacecraft position.
  - Images as fine as 1 cm/pixel in orbit
  - Much more precise than the ground-based observations, but shorter baseline.
  - Clear YORP detection required ~ 1 year





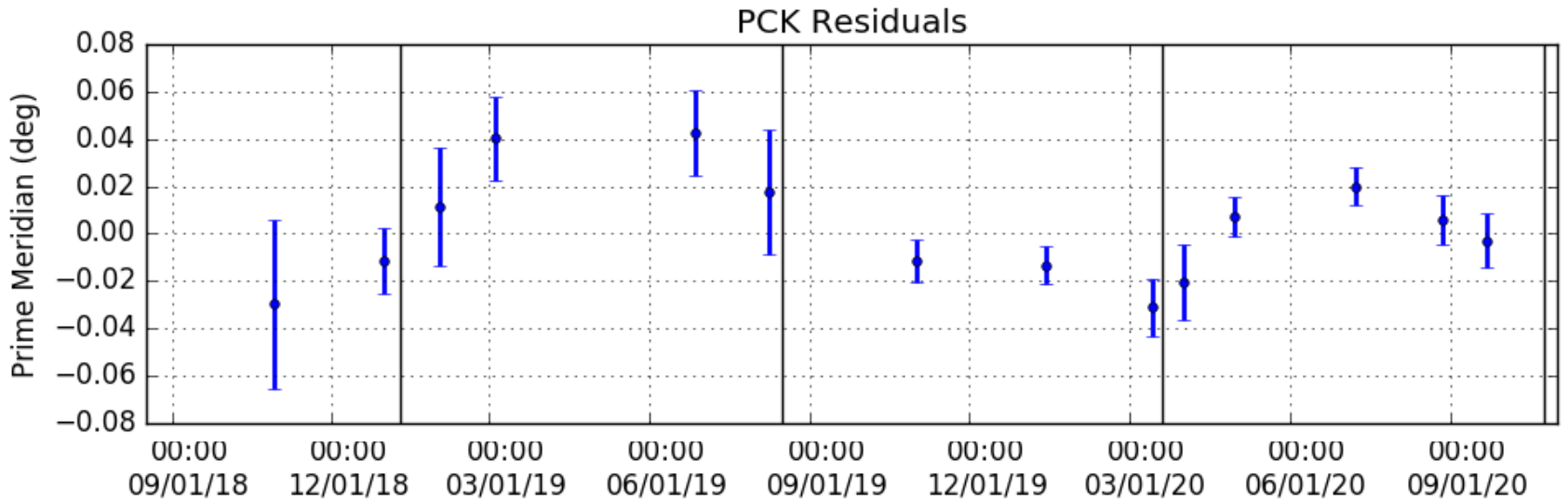
Rotation Solution Residuals w/ 3-sigma Uncertainty Bounds

- Removing the Average acceleration of 4 x 10^{-6} deg/day/day gives nearly flat residuals.
- Difficulty in comparing photometric regimes (OREx vs ground-based) increases phase uncertainty in ground-based data.
- Hint but no statistically significant change in acceleration rate.



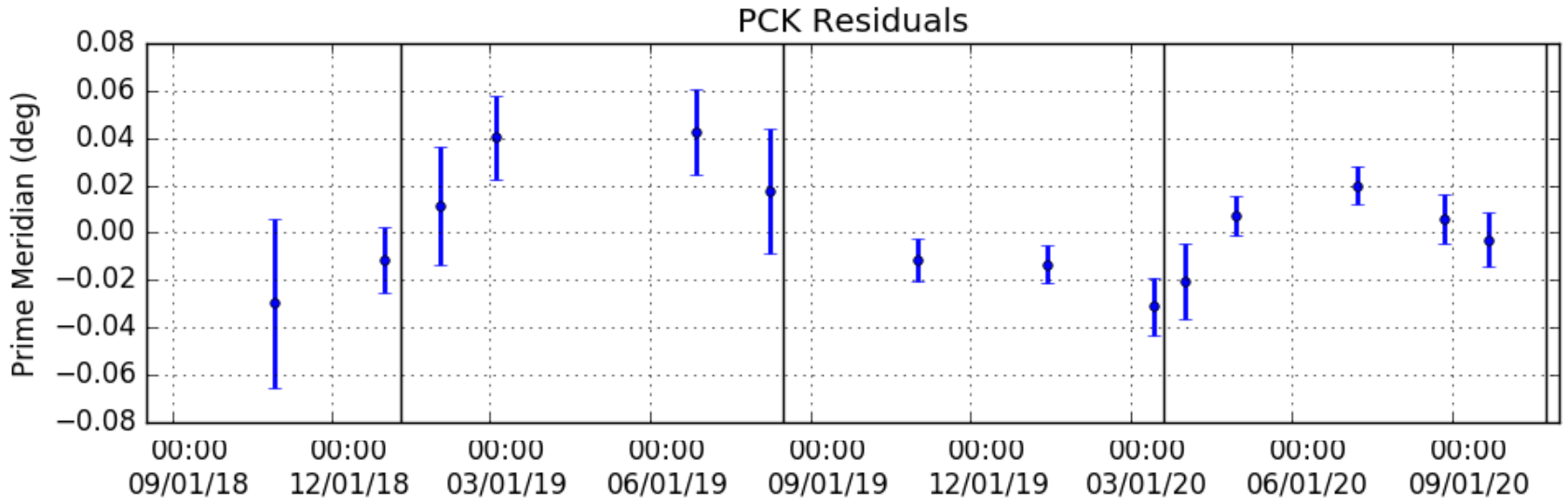
Rotation Solution Residuals

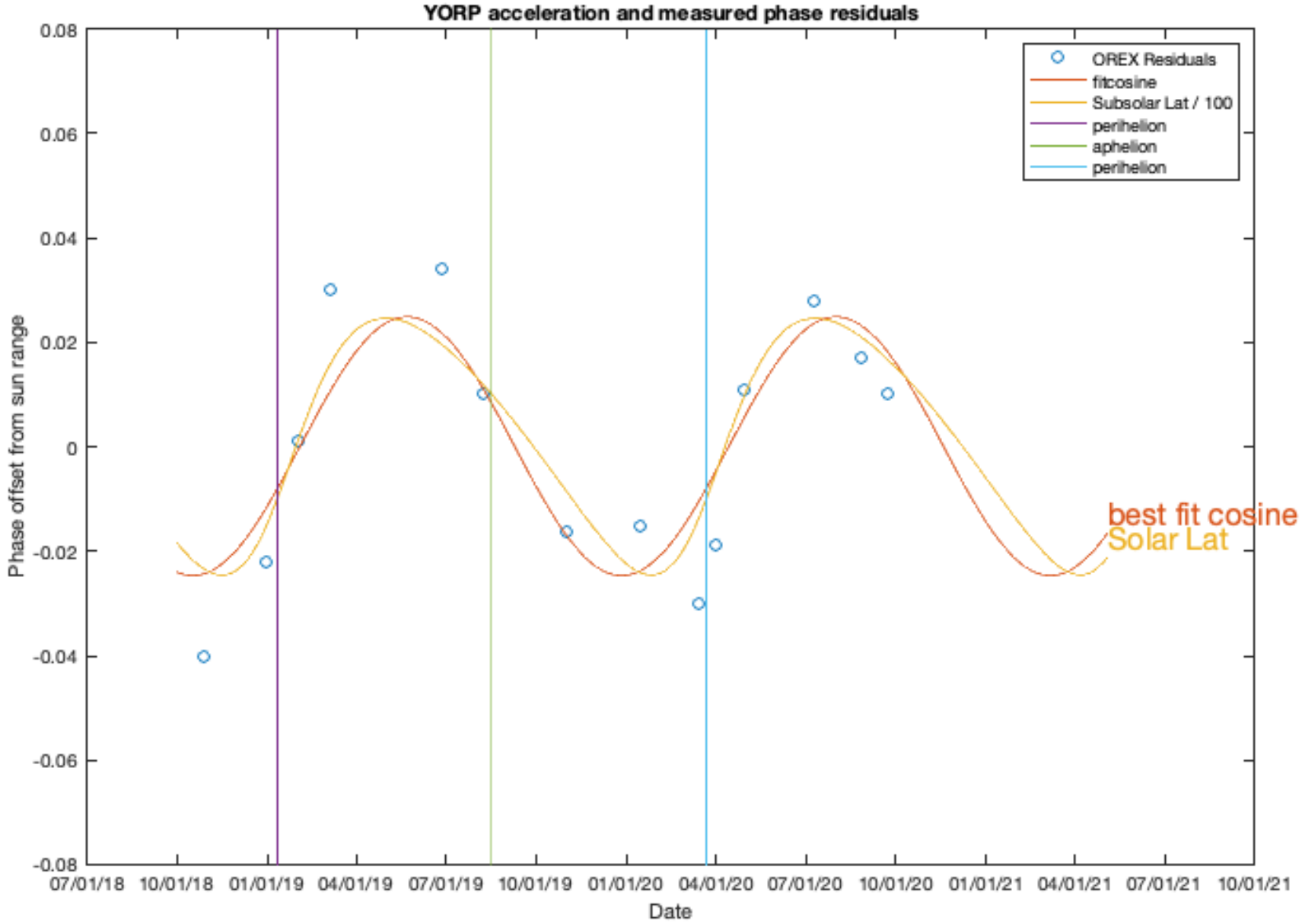
- Now blow up proximity operations.
- There appear to be ~ sinusoidal residuals with a period of 1 Bennu year



Rotation Solution Residuals

- Now blow up proximity operations.
- There appear to be ~ sinusoidal residuals with a period of 1 Bennu year
- Torque $= G/R^2[C_0 + C_1 \sin(i)\sin(\omega + f)]$
- $\Delta\theta = -\frac{(1-e^2)G}{n\,h\,l}\, C_1 \sin(i)\sin(\omega + E)$
- C_1 is differently dependent on shape / mass




YORP acceleration and measured phase residuals
OREX Residuals
fitcosine
Subsolar Lat / 100
perihelion
aphelion
perihelion
best fit cosine
Solar Lat
Phase offset from sun range
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
07/01/18
10/01/18
01/01/19
04/01/19
07/01/19
10/01/19
01/01/20
04/01/20
07/01/20
10/01/20
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Date

- Variation along orbit finally proves this is YORP
  - Or at least, something that depends on solar radiation.
- Torque $= G/R^2[C_0 + C_1 \sin(i) \sin(\omega + f)]$
- C_0 and C_1 depend differently on shape / mass
  - We will be examining those details soon.

Long Term Implications

- Bennu (and Ryugu) have obliquities very near 180 degrees, but are neither rotating near breakup nor stalled.
- Bennu's rotation is accelerating fast enough that it would break up in about 1 million years.
  - Bennu has surface features that appear to be much older than 1 million years old, predating its history in near-Earth space, as well as some that could be driven by recent YORP-induced slope changes (e.g., Jawin et al., 2020).
  - No clear sign of body-wide mass movement
- It does not appear likely that it will accelerate to breakup.
- YORP is affecting the surface, but does not appear to drive the large-scale surface evolution.
  - Could be self-limiting (Cotto-Figueroa 2015)
  - Some similar objects **are** spinning near breakup.