Shape, Orientation and Colors Combined approach for Asteroids

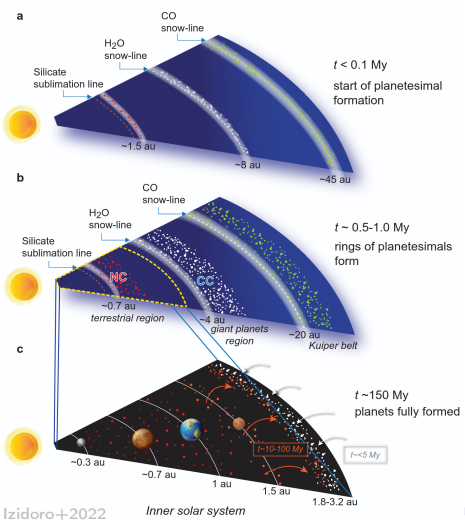
Odysseas Xenos

June 9, 2026

Asteroids: the earliest witnesses of Solar system formation

Planetesimal formation

- Gas & dust → pebbles
- Pebbles coagulate into planetesimals
- Planetesimals form the planets
- Asteroids: leftovers of this process



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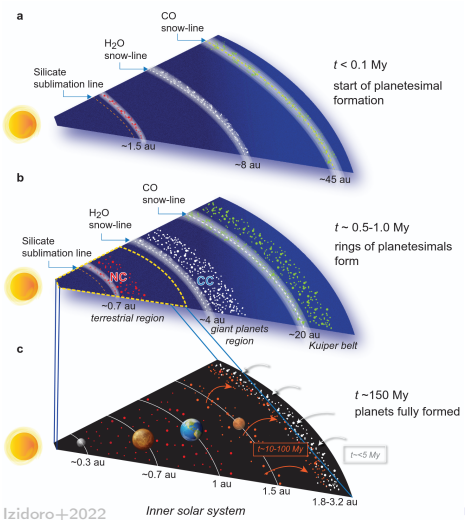
Asteroids are relics

- Little to no compositional evolution
- Reflect the early conditions



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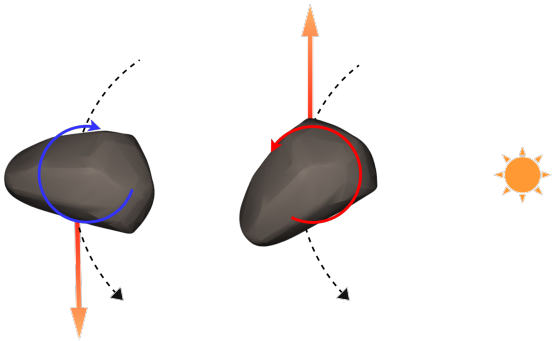
But this image has since been blurred

- Planet migration
- The Yarkovsky effect (P_{rot}, Ψ)



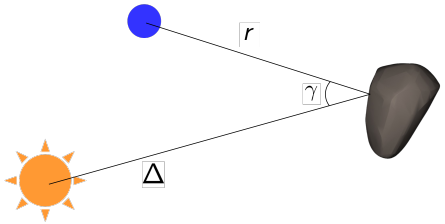
Imbalance between detections and characterization

- Physical properties at scale are important
- 1.4 mil. known SSOs
  - 11% with a taxonomic type
  - 5% with a spin axis orientation
  - 3% with a rotational period SsODNet
  - (+5 mil. with LSST) Kurlander+2025

Extracting physical properties

Color and phase parameters:

- Brightness varies with distance and phase



Extracting physical properties

Color and phase parameters:

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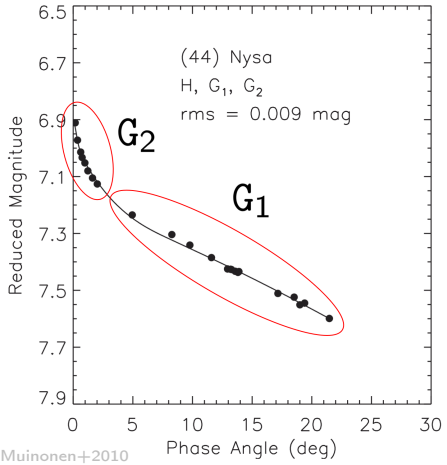
- $\mathtt{HG_1G_2}$ model

$$H = m - f(r, \Delta) - g(\gamma)$$



Muinonen+2010

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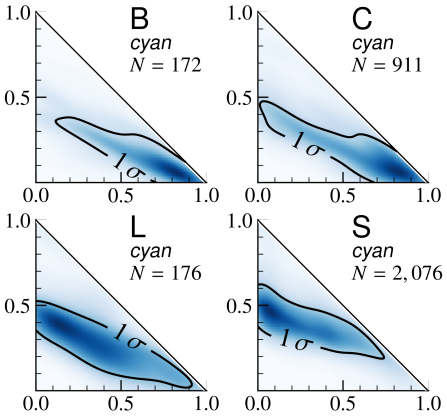

Mahlke+2022

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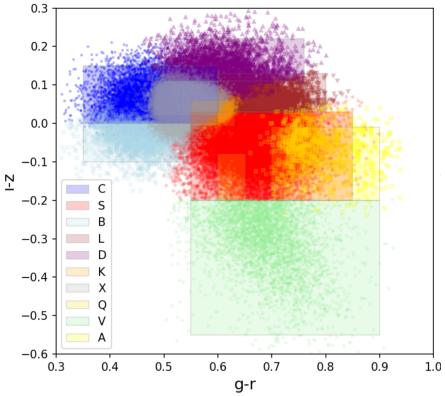

Sergeyev+2021

Extracting physical properties

Color and phase parameters:

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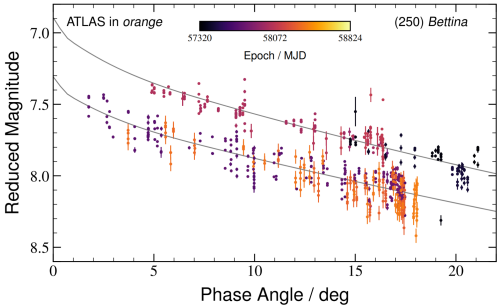
$$H = m - f(r, \Delta) - g(\gamma)$$

- Shape & rotation affect the lightcurves
- There is variation per apparition



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Extracting physical properties

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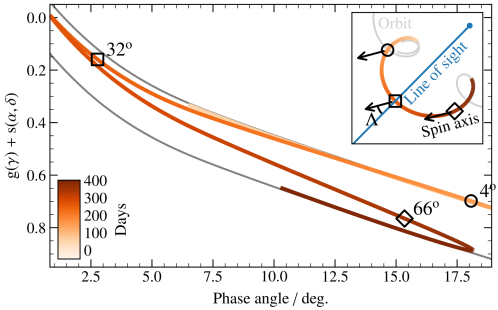
$$H = m - f(r, \Delta) - g(\gamma)$$

- Shape & rotation affect the lightcurves
- There is variation per apparition
- $\texttt{sHG}_1\texttt{G}_2$ Carry+2024

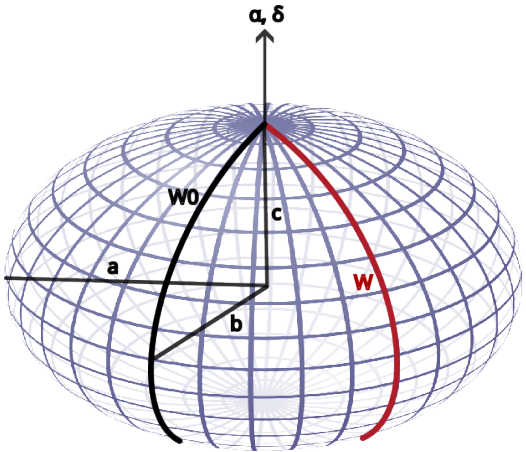
$$H = m - f(r, \Delta) - g(\gamma) - s(\alpha, \delta)$$
$$s(\alpha, \delta) = 2.5\log_{10}[1 - (1 - R)|\cos\Lambda|]$$



But we are still lacking rotational period and spin axis orientation

Shape, Orientation and Colors Combined approach for Asteroids

Introducing SOCCA

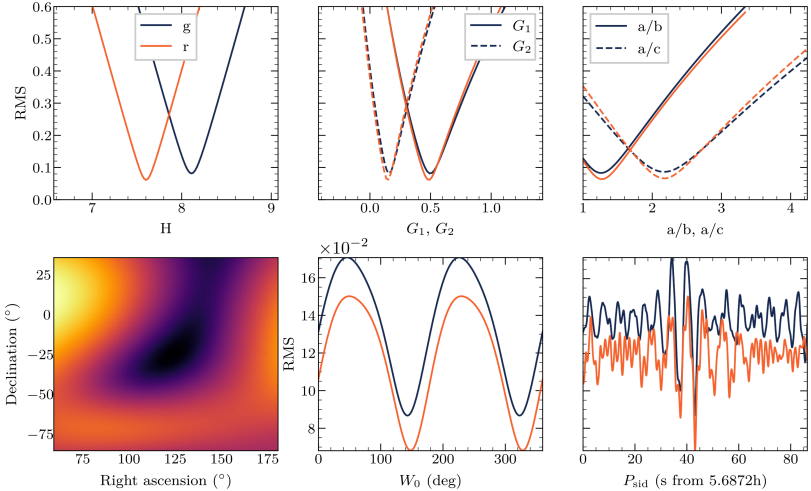


$$H = m - f(r, \Delta) - g(\gamma) - \mathcal{A}$$

$$\mathcal{A} \propto F(\alpha, \delta, a/b, a/c, W, P_{\text{sid}})$$

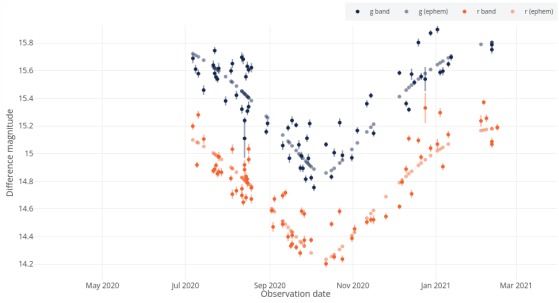
$$W = W_0 + \frac{2\pi}{P_{\text{sid}}}(t - t_0)$$

SOCCA Convergence



Rotational period

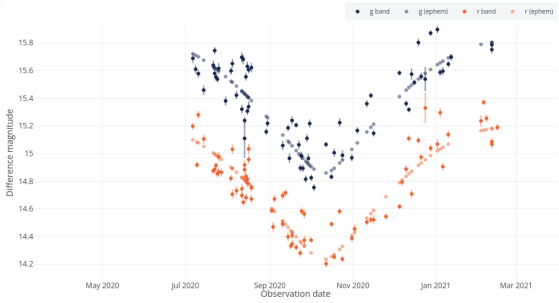
- Initial guess from L-S periodogram



(624) Hektor, ztf.fink-portal.org

Rotational period

- Initial guess from L-S periodogram
- △ Synodic vs Sidereal period...



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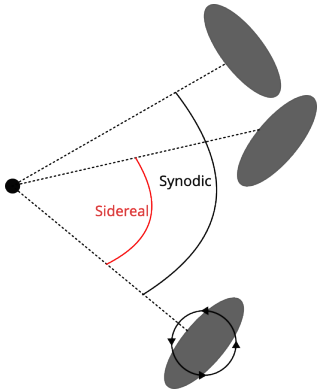
From observed to physical rotation periods

- Photometry: **synodic** period
- True rotation: **sidereal** period
- For hour-long periods, they can differ by 10s of seconds



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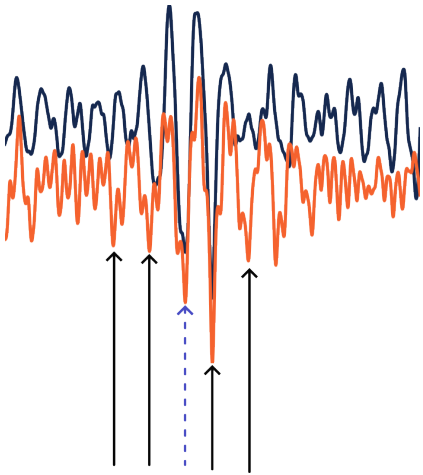
△ We therefore explore a small range of periods around the measured value during shape and spin inversion



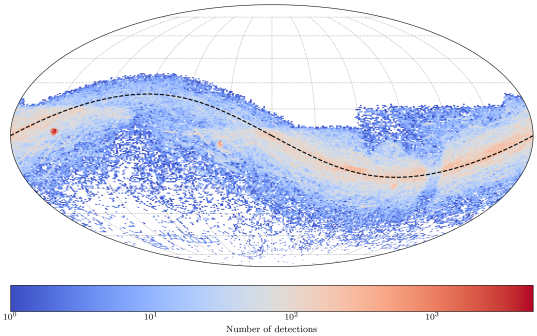
Generated lightcurves

SORCHA Merritt+2025

- Simulates SSO photometry
- Samples lightcurves like LSST would
- 10 year baseline

Objects generated [a]

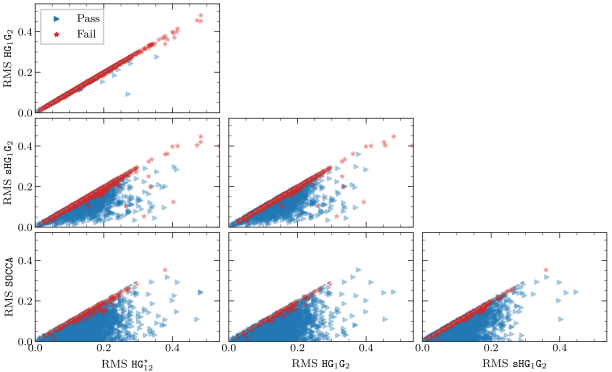
- 500 SSOs / dynamical class
- 7 dynamical classes (NE, I,M,O MB, Cen, Tro, KBO)
- Parameters from SSODNET Berthier+2023
- a/b & a/c from DAMIT Ďurech+2010



[a] https://github.com/dirac-institute/sorcha-addons/pull/40

Model residuals

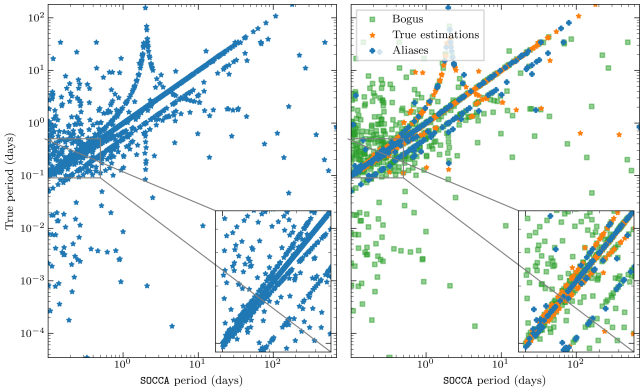
- Fit with SOCCA, $\mathtt{sHG_1G_2}$, $\mathtt{HG_1G_2}$, $\mathtt{HG}^*_{12}$
- SOCCA: $3N_F + 6$ parameters
- Hierarchical testing + F-test
- 88.5% favor SOCCA $\rightarrow$ not overfitting



Parameter retrieval

Rotational period

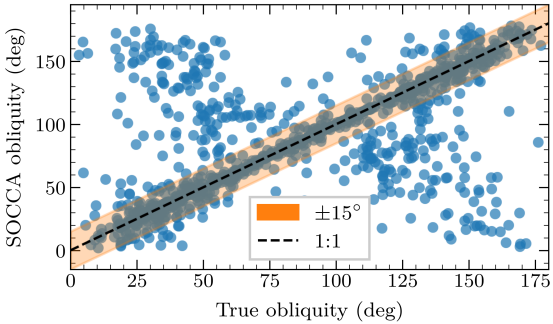
- Identify aliases and $2\times$ frequency
- Applied quality score cutoff
- Purity: 60.4% $\rightarrow$ 75.8%



Parameter retrieval

Spin axis orientation

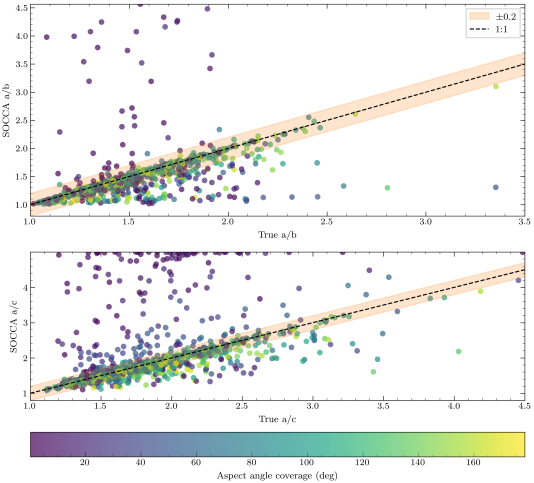
- 68.5% within 15°
- Failures: wrong period / $\Delta\gamma < 15°$
- Errors mostly mirror solutions $(\alpha_0 + 180°, -\delta_0)$



Parameter retrieval

Shape

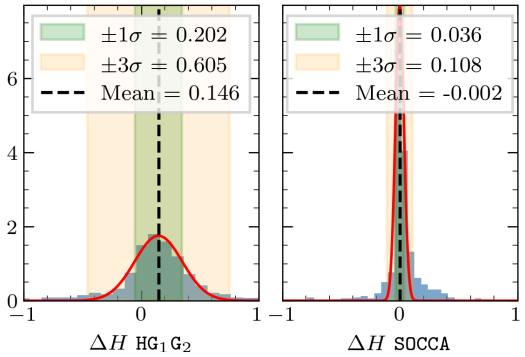
- Success if within ± 0.2 of true value
- Recovery: 83.3% (a/b), 67.4% (a/c)
- a/b constrained by rotation amplitude
- a/c constrained by aspect-angle variations
- Limited viewing geometry reduces recovery



Parameter retrieval

H, G_1 and G_2

- More accurate H
- Much tighter G_1-G_2 distribution
- Better separation of taxonomic types
- shape and spin variability in the mode



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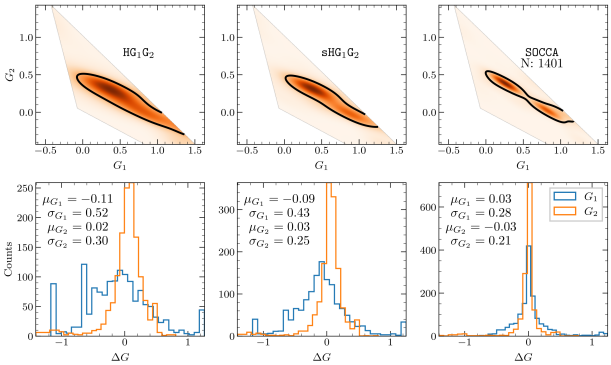
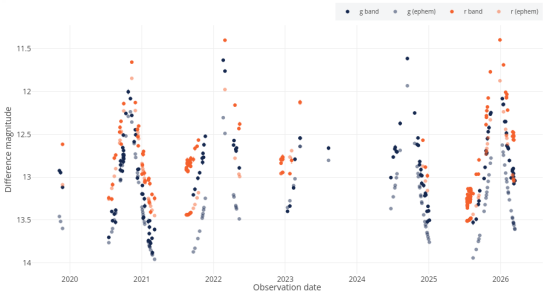


Real data validation

Dataset

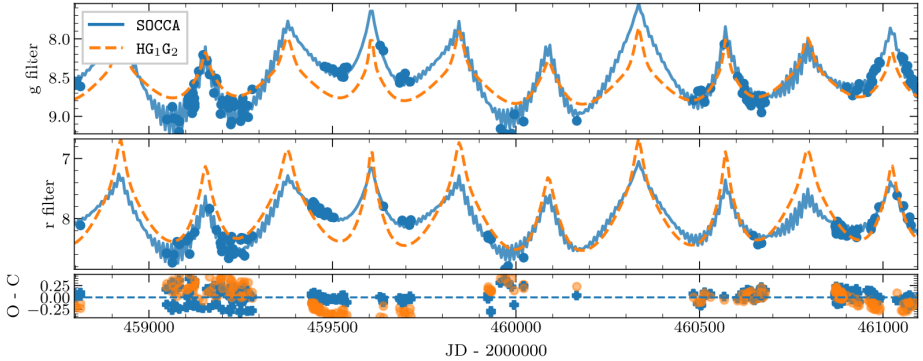
- Asteroid (45) Eugenia
- 265 ZTF measurements
- 2019-2026 baseline



Real data validation

Model comparison

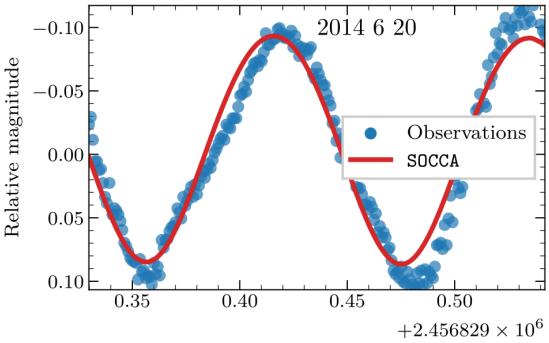
- Compare SOCCA and HG_1G_2
- SOCCA $\rightarrow$ smaller residuals
- Better brightness modeling



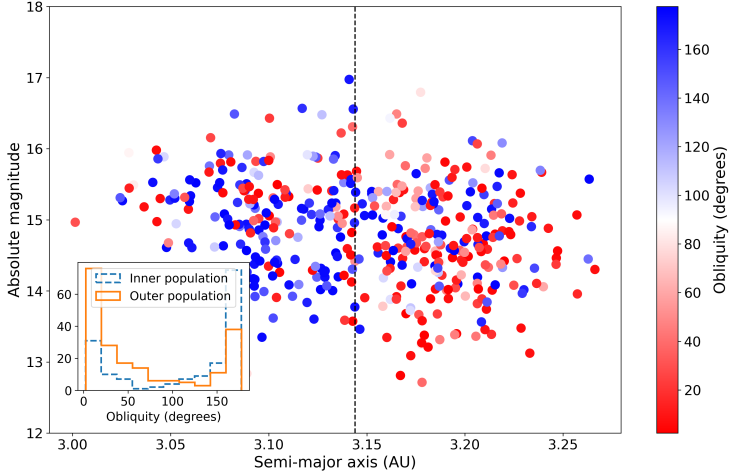
Real data validation

Dense lightcurve check

- Validate with DAMIT lightcurves
- Model propagated to epochs



Real data validation



Next steps

FiNK implementation

- 7 years of ZTF
- Real-time calculation of properties

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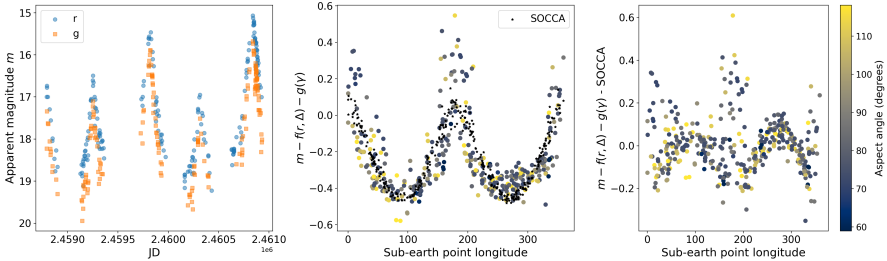
Put in numbers:

- 500,000+ SSOs in ZTF + ATLAS
- 100,000s of properties to be estimated

(8474) Rettig



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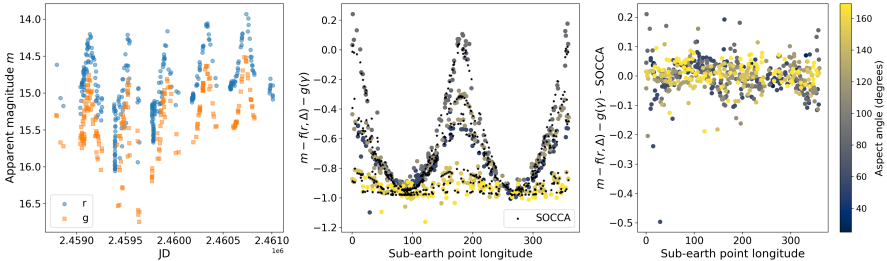
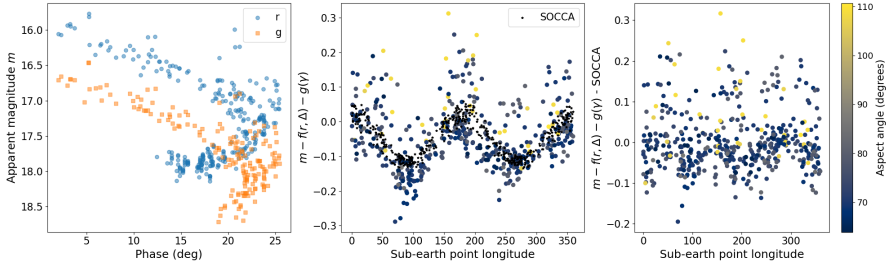
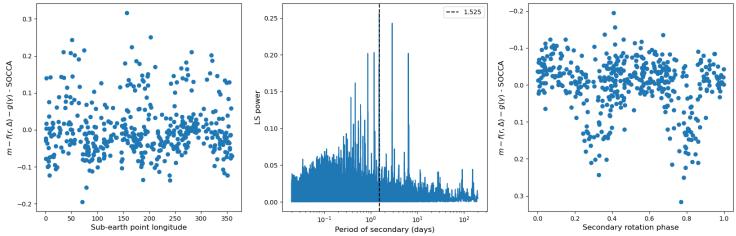


(3782) Celle


Apparent magnitude m
Phase (deg)
r
g
$m - f(r, \Delta) - g(\gamma)$
Sub-earth point longitude
SOCCA
$m - f(r, \Delta) - g(\gamma)$ - SOCCA
Aspect angle (degrees)


$m - f(r, \Delta) - g(\gamma)$ - SOCCA
Sub-earth point longitude
LS power
1.525
Period of secondary (days)
Secondary rotation phase

SOCCA is available at https://github.com/astrockers/socca-tune as an extension to https://github.com/astrockers/phunk

Thank you!