Occultations and the Size and Density of Asteroids

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Small bodies in the Solar System formation context

- SB are remnants of the early stages of planetary formation.
- They contain information about these processes.
- Trigger (new/revised) theories on the formation and evolution of our Solar System (GTM, NM).
- SS history more dynamic than thought 20+ yrs before.
Based on TC to (diameter, mass) calculation. Wish: statistic sample based on real estimates.
SB: different but related domains

- Orbit and spin state
- Composition
- Physical parameter (size, mass, bulk density, macro porosity, etc.)

- Dynamical (LT) studies, YE,...
- In situ, spectra (VIS/VNIR) => TC, meteorites
- Size: multi-domain (e.g. occultations)
- Mass: dito (e.g. astrometric)
Density of asteroids

- Fundamental property for the understanding of the composition and internal structure.
- Directly: (mean bulk) density = mass / volume.
- Indirectly: Mutual events of binary systems.
- Deduce it from TC associated density.
Asteroids – TC – Meteorites - Link

- **Taxonomic Classes** (TC): classification scheme based on VIS and VNIR spectra
  - Chapman, Morrison, Zellner (1975)
  - Tholen (1984): 3 groups (C/S/X), 14 types
  - Bus-DeMeo (2009): 24 classes
  - SMASS, S3OS2,...

Typical values for density:
- $C = 1.38 \text{ g/cm}^3$
- $S = 2.71 \text{ g/cm}^3$
- $M = 5.32 \text{ g/cm}^3$
  (Krasinsky et al. 2002)

**Meteorites**

- Typical densities ($\text{g/cm}^3$):
  - Chondrites: 3.2-3.4
  - Carbonaceous chondrites: 2.1-3.5
  - Stony irons: 4.3 – 4.8
  - Iron: 7-8
  - + lot of sub-types!

Find link between TC and meteorites. Then you can examine this piece of asteroid in the laboratory.
Volume / Size / (mean, eff., equiv.) Diameter

- Volume (Sphere, MacLaurin, Jacobi) = f(1-3 param.), e.g. \( V = V(D) = \frac{4}{3} \pi \frac{D}{2}^3 \)
- Non-spherical body: define a mean/equivalent/effective diameter \( D \) for it, where:
  - a sphere with that diameter has the same volume as the body.
  - a sphere with that diameter has the same surface as the body.
- Density => \( D_{\text{equiv}(V)} \) is needed.
- Caution: check radiometric diameter if \( D_{\text{equiv}(V)} \) or \( D_{\text{equiv}(A)} \) is given.
- I will use the terms diameter, size, volume interchangeable for the same concept.
Diameter/Size/Volume estimates

- Crude estimate from H and assumed (TC) geometric albedo p:  
  $D \text{ (km)} = 1329 \, p^{-0.5} \times 10^{-0.2H}$

- Radiometric (thermal modeling, e.g. STM and NEATM): IRAS, AKARI, Spitzer, WISE.

- 2D from occultations.

- 3D model from LC inversion (ADAM, KOALA, SAGE) need to be scaled for physical size => OCC's!

Multi-data: LC, OCC, direct imaging, radar (NEO).
Diameter estimate methods

![Graph showing frequency of different diameter estimation methods]

- ADAM
- BrKUp
- FlyBy
- H-mag
- IAU
- Img
- Img-PSF
- Img-TE
- KOALA
- LC+Occ
- NEATM
- Occ
- PheMu
- Radar
- STM
- TPM

frequency
Relative error for diameter estimates

Excluding outlier

Including outlier

Sample: ~ 4000 estimates
Benefit of asteroidal occultation observations

- **Size** *(directly or via multi-data). (sub-)km level!*
- **2D-Profile / Shape**
- **(sub-) mas astrometry**
- **Binary, moons, rings etc.**
- **Increasing data set:**

Number of OCC+ is growing significantly (not only since Gaia, but boosted by Gaia).
Mass estimates

- Methodically usually harder to derive as size.
- More data needed (more objects, more estimates per object).
- Gaia prospects:
  - ~ 36 < 10%
  - ~ 150 < 50%
Mass estimates

Deflec : Mutual encounter
Ephem: JPL DE, INPOP
astrometric methods
Relative error for mass estimates

Excluding outlier

Excluding 55 records > 200%

Sample: ~ 1700 estimates
SiMDA catalog of densities

SiMDA ‘plain’: no individual D,M selection for a ‘best value’ estimate (TBD and/or by user), just outlier rejection. EVM tend to larger standard errors.

But: only ~ 300 estimates
Uncertainty of derived density

- The contribution of diameter uncertainty easily overwhelms that of the mass:
  \[ \frac{\Delta \rho}{\rho} = \sqrt{\left(\frac{\Delta M}{M}\right)^2 + 9\left(\frac{\Delta D}{D}\right)^2} \]
Main conclusion

- We need more and more accurate and reliable densities!
  - => Volumes (diameters)
    - Occultations
    - Light Curves
  - => Mass estimates

- Formal (post fit) errors can be underestimated (wrt to mass and diameter).
  - Diameter / mass / density data probably biased by used methods and also by observational constraints.
Research: where are the (individual) data !?

- No machine-readable compilation of individual mass estimates including errors.
- Diameter: different (often machine-ready) data sets available, but many individual results only in literature. Need to be evaluated, joined in data set including error estimates, etc.
- No machine-readable compilation of all densities including the individual diameter and mass estimates and their errors.
- Hard to get a (quick and easy) overview / common picture about all diameter, mass and density including error estimates publications for an object.
Existing work on densities

- Asteroid I-IV.
- Some individual research and compilations on asteroid masses.
- Several data set on diameters.
- Latest compilation: paper by Carry 2012.

(Incomplete list)
SiMDA – Data Archive and Web Portal

At present

- Initial motivation: own mass determination of asteroids => get an overview about status quo.
- Data: Manual, scripted (parser) and OCR based acquisition of ~4000 diameters, ~1750 mass estimates, ~2600 tax and dyn. classes, ~230 references.
- Application: Django (Python) web application.
- Note: SiMDA is still in early state.

Roadmap

- Reach v1.0 until EPSC 2020 ... ;-) 
- More data (still incomplete).
- Dynamical (sub)classes.
- Catalog: improve ‘Best value’.
- Additional online (on the fly) analysis features.
- Other data exchange formats (VO tables etc.).
- User suggestions ...
SiMDA – Size, Mass and Density of Asteroids (but also TNOs, Comets, ...)

Short live preview / presentation ...
Summary / Takeaway

- Number of diameter, mass and density estimates has grown about one order of magnitude since *Asteroids III*.
- Still just a tiny fraction (and biased?).
- Mass estimates were crucial in the past in terms of quantity but also quality (u.e. errors). Can / will improve due to:
  - better astrometry (talk by J. Fereirra)
  - better errors models
  - more data (surveys)
  - Gaia observations of asteroids
- As consequence the diameter estimates will become (more) crucial for the density accuracy in many cases.
- Radiometric method may have significant (systematic) errors.
- LC+OCCs reliable independent method, significant (continuous) amateur contribution is possible (photometry and occultations).
- Dedicated data archives and analysis tools like SiMDA help to reveal issues and to find ‘best values’.
Thank you for ... 

- your work on asteroidal occultations. Accurate and reliable diameter values are very important for SB science!
- your work on asteroidal (rotation) light curves.
- your astrometry (+ sparse photometry).
- using SiMDA and helping to improve it.
- your attention!