Asteroid Mass Determination

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Introduction

Knowledge of asteroid masses (and densities) is important for ...

- Better estimates of mean bulk densities, porosity etc. for different taxclasses (S,C,M etc. type asteroids)

- Understanding the dynamics and evolution of minor bodies and the solar system itself. Adjusting modell parameters

- Generation and improvement of high accurate planetary ephemerides like DExxx, INPOPxx etc.

  => high precision asteroidal ephemerides (spacecraft targets, occultation predictions, etc.)

- Planning and realizing space missions (fly-by, in-orbit)
Methods

► Gravitational asteroid-asteroid interaction:
  - culmulative effects (resonances)
  - deflection events (single / multiple) (close and/or slow encounters)

► Analysis of planetary motion (e.g. perturbations on Mars)
► Orbital motion of asteroidal satellites / binary systems: observations by spacecrafts, HST, or ground based (AO)
► Gravitational asteroid-spacecraft interaction
► Ground based radar observations (binary systems, asteroidal satellites)
  Problem: 1/r **4 drop of reflected signal
Least-squares fit to the observations

Correction $\Delta M$ to the mass of the (massive) perturber is computed along with the corrections $\Delta E = (E_1, \ldots, E_6)$ of the six initial values (or osculating elements) of the „test“ (= deflected) asteroid.

These corrections are the solution of a system of linear equations:

$$ P \Delta E + Q \Delta M = R \quad (1) $$

$P$: matrix of partials $\partial C_i / \partial E_k$ (Coordinates $C = RA, DE$)
$Q$: matrix of partials $\partial C_i / \partial M$
$R$: matrix of residuals (O-C) in RA, DE
  for $i=1,\ldots,N$ observations and $k=1,\ldots,6$ elements / initial values

Usually solved by the method of least-squares (LSQ Fit)
This differential orbit correction is performed by an so called N-body program:

1. Integration of the test asteroid taking into account the perturbations by:
   - the major planets
   - if applicable further perturbing asteroids
   - the perturbing (massive) asteroid which mass should be improved
   - other forces like relativistic effects etc.
2. Computing the residuals for the observations
3. Solving the equations of conditions (1)
4. Applying the corrections ($\Delta E$, $\Delta M$)
5. (Re)weighting / rejecting observations
6. Next iteration of computation until stable result is achieved
Difficulties

- Ceres contains ~1/3 of the mass of the main belt, but this is only ~1% of the mass of our moon

- As the involved masses are very small, the gravitational interactions are usually rather weak

- Numerical issues (convergence, bad conditioned equation systems, correlations, underestimated errors)
  - Careful review / preprocessing of observations
  - Careful rejection of observations (requires some experience)
**Related topics**

**Diameters and shapes (=> bulk densities):**

- Observation of occultations (diameter, profile/shape) *
- Lightcurves (shape by lightcurve inversion) *
- Radiometric and polarimetric methods (IRAS, ground based)
- Resolved imaging (HST, AO, in-situ)
- Other methods (speckle interferometry, radar, etc.)

* Mainly amateur contributions!
The past ~40 years

- First asteroid mass (Vesta) computed by Hertz in 1966

- First ~20yrs: mass estimates for only four asteroids have been published (Ceres, Pallas, Vesta, Hygiea)

- 2008: mass estimates for about 55 asteroids
  
  Max: 4.8E-10 (1 Ceres)
  Min: 1.9E-14 (189 Phthia : asteroid-asteroid perturbation)
## Examples (classical methods)

<table>
<thead>
<tr>
<th>Asteroid</th>
<th>Test asteroid</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>(2) Pallas</td>
<td>(1) Ceres</td>
<td>Schubart 1974, 1975</td>
</tr>
<tr>
<td>(10) Hygiea</td>
<td>(829) Academia</td>
<td>Scholl, Schmadel, Röser 1987</td>
</tr>
</tbody>
</table>
Examples (non-classical methods)

<table>
<thead>
<tr>
<th>Asteroid</th>
<th>Method</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>(243) Ida</td>
<td>Galileo spacecraft / satellite</td>
<td>Belton et al. 1995,</td>
</tr>
<tr>
<td>1.9E-14</td>
<td></td>
<td>Petit et al. 1997</td>
</tr>
<tr>
<td>(121) Hermione</td>
<td>AO / satellite</td>
<td>Marchis et al. 2005</td>
</tr>
<tr>
<td>2.705E-12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(25143) Itokawa</td>
<td>Hayabusa spacecraft</td>
<td>Fujiwara et al. 2006</td>
</tr>
<tr>
<td>1.760E-20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2003 YT1</td>
<td>Radar / binary system</td>
<td>Brooks et al. 2006</td>
</tr>
<tr>
<td>6.38E-19</td>
<td></td>
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Future prospects (GAIA)

► GAIA (due for launch in late 2011) will observe ~300000 (mainly MB) asteroids down to V ~20 with sub-mas to mas precision

► About 100 potential perturbers (mass determinations) during the 5yr operational lifetime

► GAIA will also directly measure sizes for ~1000 objects

► And much more... GAIA will have a major impact on fundamental astronomy, solar system etc.
Authors results (presented here in 2005)

<table>
<thead>
<tr>
<th>Asteroid</th>
<th>Test asteroid(s)</th>
<th>Mass [Solar Mass Units]</th>
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</thead>
<tbody>
<tr>
<td>(16) Psyche</td>
<td>(13206) 1997 GC22</td>
<td>(2.5 ± 0.2) E-11 (1.1 ± 0.04) E-11 (Bear 2008)</td>
</tr>
<tr>
<td>(29) Amphitrite</td>
<td>(987) Wallia (6904) McGill</td>
<td>(5.9 ± 0.6) E-12 (5.9 ± 0.3) E-12 (Bear 2008)</td>
</tr>
<tr>
<td>(121) Hermione</td>
<td>(278) Paulina (5750) Kandatei</td>
<td>(3.3 ± 1.1) E-12 (2.71 ± 0.15) E-12 (Marchis 2005)</td>
</tr>
<tr>
<td>(804) Hispania</td>
<td>(1002) Olbersia</td>
<td>(2.2 ± 0.9) E-12 (2.0 ± 0.4) E-12 (Bear 2008)</td>
</tr>
</tbody>
</table>
Authors preliminary results (2008)

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<th>Asteroid</th>
<th>Test asteroid(s)</th>
<th>Mass [Solar Mass Units]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(13) Egeria</td>
<td>(14689) 2000 AM2</td>
<td>~5E-12 (in work)</td>
</tr>
<tr>
<td>(15) Eunomia</td>
<td>(50278) 2000 CZ12</td>
<td>(1.4 ± 0.3) E-12</td>
</tr>
<tr>
<td>(16) Psyche</td>
<td>(13206) 1997 GC22</td>
<td>(1.7 ± 0.7) E-11</td>
</tr>
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</table>
Observation proposals


Mail list posts by the author

Authors website: http://sky-lab.net | http://obsnn.de

2008-04-08.86: (1) Ceres / (104758) 2000 HR18
   d=0.0028 AU   Vrel=3.353 km/s

2008-04-23.39: (349) Dembowska / (135356) 2001 TF83
   d=0.0012 AU   Vrel=2.640 km/s

2008-10-20.03: (238) Hypatia / (128251) 2003 SA247
   d=0.0016 AU   Vrel=1.079 km/s

Please monitor upcoming events and observe perturber and test asteroid to ensure that a good astrometric data sample is available over some weeks around the encounter

You can contribute to professional science with your dedicated observations! Thank You!