Mass Determination of Asteroids

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Mike Kretlow

Introduction

Knowledge of their masses (and densities) is important for …

- Estimation of their compositions.
- Understanding the dynamics and evolution of minor bodies and the solar system itself.
- High-accurate planetary ephemerides like DE403, DE405 etc.
  => high-accurate asteroidal ephemerides
  (spacecraft targets, occultation predictions, mass determination etc.).

Methods

- Gravitational asteroid-asteroid interaction:
  => culmulative effects (resonances).
  => single deflection events.
- Analysis of planetary motion (perturbations on Mars).
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- Orbital motion of asteroidal satellites: observations by spacecrafts or ground based (AO), HST.
- Gravitational asteroid-spacecraft interaction.
- Ground based radar observations (binary asteroids, asteroidal satellites).
  Problem: r **-4 drop of reflected signal => Arecibo.

Least-squares fit to the observations

- Correction ΔM of the mass of the perturber is computed along with the corrections ΔE=(E1,…,E6) of the six initial values (or osculating elements) of the test asteroid.

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

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

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 and DE
for i=1,…,N observations and k=1,…,6 elements or init. values.

Usually solved by the method of least-squares.

This differential orbit correction is performed by an so called N-body program:

- Integration of the test asteroid taking into account the perturbations by:
  - the major planets,
  - if applicable further perturbing asteroids,
  - the perturbing asteroid which mass should be improved,
  - other forces like relativistic effects etc.
- Computing the residuals for the observations.
- Solving the equations of conditions (1).
- Applying the corrections => next iteration of computation.

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 masses are very small, the gravitat-ional interactions are rather weak.

Related topics

Diameters and shapes (determination of bulk densities):

- Observation of occultations
- Lightcurves
- Radiometric and polarimetric methods (IRAS, ground based)
- Resolved imaging (HST,AO,in-situ)
- Some others (speckle etc.)

The past ~40 years

- First mass determined by Hertz in 1966.
- 1966-1989: masses for only for 4 asteroids were known (Ceres,Pallas,Vesta,Hygiea).
- Up to now: masses for about 30 asteroids have been determined.

Note: DE403 etc. considers estimates for about 300 asteroids.

Early works / classical methods

Asteroid	Test asteroid	References
(4) Vesta	(197) Arete	Hertz 1966, 1968, Schubart & Matson 1979
(1) Ceres	(2) Pallas, (4) Vesta	Schubart 1970, 1971, 1974
(2) Pallas	(1) Ceres	Schubart 1974,1975
(10) Hygiea	(829) Academia	Scholl, Schmadel, Röser 1987

Newer works / methods

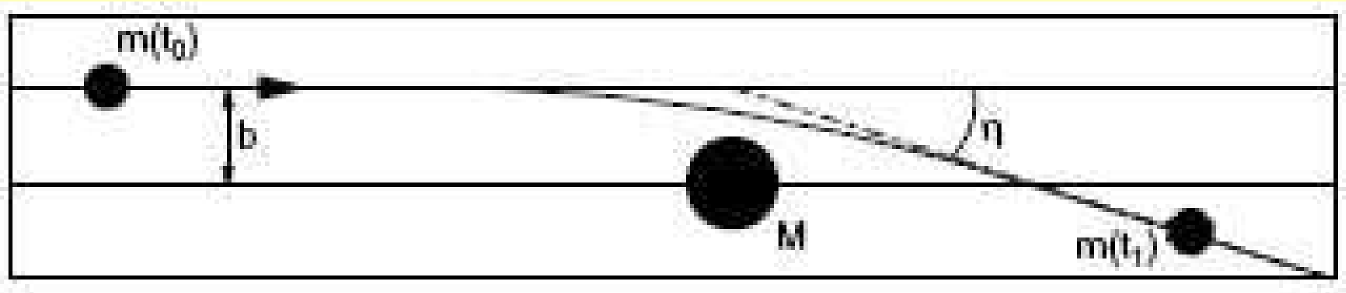
Asteroid	Method	References
(2) Pallas	Mars / Viking data	Standish & Hellings 1989
(243) Ida	Satellite S/1993(243)1 Dactyl	Belton et al. 1995
(253) Mathilde	NEAR tracking data	Yeomans et al. 1997
(433) Eros	NEAR tracking data	Yeomans et al. 1999
(45) Eugenia	Satellite S/1998(45)1	Merline et al. 1999

Own work (presented here)

Asteroid	Test asteroid(s)	Mass [Solar Mass Units]
(16) Psyche	(13206) 1997GC22	(2.5 ± 0.2) E-11
(29) Amphitrite	(987) Wallia and (6904) McGill	(5.9 ± 0.6) E-12
(121) Hermione	(278) Paulina and (5750) Kandatei	(3.3 ± 1.1) E-12
(804) Hispania	(1002) Olbersia	(2.2 ± 0.9) E-12
(7348) 1993FJ22	(7562) Kagiroino-Oka	(8 ± 46) E-16 [just for fun] Expected: 5E-15

(29) Amphitrite

- Classical asteroid-asteroid method: single deflection events.
- Encounter with (6904) McGill on 1985/06/15 with dmin=0.00933 AU and vrel=0.571km/s. Discovered in 1990 (Börngen @ Tautenburg), but prediscovery observations in 1951,1955,1982. 1985/06/13 on UKST plates [unfortunately not provided].
- Encounter with (987) Wallia on 1994/03/03 with dmin=0.00245 AU and vrel=3.194 km/s. Discovered 1899. Obs. arc: 1922-2004.
- Deflection angle ~ (M+m) / dmin * vrel**2.



Results

Test asteroid	Mass #29 [E-12 SMU]	Density [g/cm**3]	RMS [arcs]	Obs. acc./total
(987) Wallia	6.1 ± 1.7	2.4 ± 0.7	0.461	541/683
(6904) McGill	5.9 ± 0.6	2.4 ± 0.3	0.511	349/367
Weighted mean value	5.9 ± 0.6	2.4 ± 0.3		

- IRAS diameter (212.2 ± 6.8) km
- S-class asteroid, expected mean bulk density:
  2.7 (2.4) g/cm**3

dRA*cos(DE) and dDE for 987 (top) and 6904 (bottom)