The asteroids and the early Solar System

B. Carry
European Space Agency
Resume of planetary formation

Step-by-step

a. Gas & dust cloud contracts
b. Disk forms
c. Rotation, accumulation @ center
d. A star is born
e. Accretion within the disk
f. Planetary system
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**Interest of asteroids**

1. **Large population**
   - 600,000 objects (*several millions*)
   - Sample the whole Solar System [1–100 AU]
   - Sample all the compositions [rocks $\rightarrow$ ices]

2. **Primitive population**
   - *Small* objects [km]
   - Internal energy $\approx$ null
   - No endogenous activity

$\triangleright$ Direct witnesses of the early Solar System
The 1982’s view

1. Asteroid taxonomy
   - Reflectance
   - Albedo
   - 24 classes

2. Strong gradient in 1 AU
   - X : Iron cores
   - V,A : Crust & Mantle
   - S : Melted silicates
   - C : Most primitive
   - D,T : Comet nucleus?

3. Paradigm from 1982
   - Survey of 800 asteroids
   - Visible spectrometry
   - In-situ formation

Planetary formation What a Nice model Density Early Solar System KOALA Conclusion
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Bus-DeMeo Taxonomy Key

S-complex

C-complex

X-complex

Ordinary chondrites

Carbonaceous chondrites?

Nickel-iron - Stony iron - Entatites

End members

http://smass.mit.edu/busdmeoclass.html
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Relative fractions of classes

Adapted from Gradie and Tedesco, 1982
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Relative fractions of classes

Adapted from Gradie and Tedesco, 1982
Some open questions

- Late Heavy Bombardment
  - Excess cratering @ 3.8 Gy
  - Thick disk for accretion
  - Tiny fraction remains

- Planetary migration
  - Hot Jupiters
  - Migration within disk
  - Solar System?

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5/25 B. Carry, ESA, 2012-10-104
The Grand Tack & Nice model

A. Grand Tack – 100 kyr
- Jupiter inward migration
- Stopped by Saturn
- Inner Solar System

B. The Nice Model – 700 Myr
- Jupiter-Saturn interaction
- Neptune pushed out
- Outer Solar System

Overall result
- Complete mixing
- Removal of 99% mass

Walsh et al. 2011
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Gomes et al. 2005
But... and the 1982’s view?

Adapted from Gradie and Tedesco, 1982

In-situ formation?
But... and the 1982’s view?

Adapted from Gradie and Tedesco, 1982

In-situ formation?

Number instead of mass – Only largest asteroids
The era of all-sky surveys

1. Number of discoveries sky-rocketed in 30 years
   - 10,000 in 1982 ... 600,000 in 2012
   - Completeness vastly improved (2–5 km)
     ▶ Dynamic models

2. Compositional information available for thousands of asteroids
   - SDSS : visible colours for 100,000 asteroids (vs 800)
   - WISE : albedo for 150,000 asteroids (vs 2000)
     ▶ Large-scale taxonomy

3. Density is needed to convert numbers in mass
   - Limiting factor
   - How do we measure density?
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How do we measure density?

\[ \rho = \frac{M}{V} \]
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\[ \rho = \frac{M}{V} \]
Mass measurements

1. Flyby
   - Asteroid - Probe
   - **Precise** but rare

2. Satellites
   - Asteroid - Satellite
   - Precise and about common

3. Deflection
   - Asteroid - Asteroid
   - Low precision but common

4. Ephemeris
   - Asteroid - Everything
   - Low precision but common
Mass measurements

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Volume measurements

\[ \rho = \frac{M}{V} \]

- **Masses**: 287
- **Diameters**:
  - IRAS: 2228
  - AKARI: 10 000
  - WISE: 150 000
  - Gaia: 10 000
Volume measurements

\[ \rho = \frac{M}{V} \]

\[ \frac{\delta \rho}{\rho} = \sqrt{\left( \frac{\delta M}{M} \right)^2 + \left( \frac{\delta V}{V} \right)^2} = \sqrt{\left( \frac{\delta M}{M} \right)^2 + 9 \left( \frac{\delta R}{R} \right)^2} \]

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The Volume is (easily) the Limiting Factor
Summary of accuracy
Summary of accuracy

The graph shows the cumulative distribution of relative precision for both diameter and mass. The x-axis represents the relative precision (%), while the y-axis represents the cumulative distribution (%). The graph includes data points for 20%, 50%, and 100% relative precision, with values of 94%, 76%, and 60% respectively for mass. The data points are marked with the percentage of accuracy for both diameter and mass.
Summary of accuracy
Current knowledge on density

- Nickel-Iron
- Stony-Iron
- Enstatite chondrites
- Ordinary chondrites
- HED achondrites
- Carbonaceous chondrites

Diameter (km)
- 500 < \( \phi \)
- 200 < \( \phi \) < 500
- 100 < \( \phi \) < 200
- 50 < \( \phi \) < 100
- \( \phi \) < 50

Relative precision (%)
- < 20%
- < 50%
- < 100%

Taxonomy
- TNO
- X-complex
- S-complex
- C-complex
- End-members
- Comets

Mass (kg)
- 10^{14}
- 10^{16}
- 10^{18}
- 10^{20}
- 10^{22}

Density
- 0
- 2
- 4
- 6
- 8
- 10

Carry 2012

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Compositional distribution

Adapted from Gradie and Tedesco, 1982
Compositional distribution revised is radically different!

- Almost complete **mix** everywhere
- **Absence** of mixing in Hilda & Trojan

Evidences for Grand Tack and Nice models
Open questions

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End members

- ?
- ?
- ?
- ?
- ?

http://smass.mit.edu/busdemeoclass.html

No interpretation for 50%

- **Meteorite & asteroid spectroscopy**
  - Now based on 0.5–2.5 µm
  - Wider spectral range: 3–5 & 5–40 µm
  - Albedo & thermal inertia

- **More asteroid analogs**
  - Laboratory experiments
  - Recovery campaigns

- **Density determinations**
  - Binary systems (now ~50/200)
  - Accurate volume determination

Albedo biased

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Accurate volume determination

1. Direct measurements
   - **WYSIWYG** ≠ model-dependent
     - Disk-resolved imaging
     - Stellar occultations

2. Realistic 3-D shape
   - Assumptions ⇒ biases
   - Concavity ⇔ Volume
     - Lightcurves (dense & sparse)

3. Geometry completeness
   - Extensive approach
     - Mid-IR radiometry
     - Interferometry
     - Radar echoes
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The concept of KOALA
The concept of KOALA

Disk-resolved images

Direct
Indirect
Size
Shape
Spin
The concept of KOALA
The concept of KOALA

- Lightcurves
- Disk-resolved images
- Sparse Photometry
- Direct Size
- Direct Shape
- Stellar occultations

Planetary formation
What a Nice model
Density
Early Solar System
KOALA
Conclusion
The concept of KOALA

**Knitted**
- Occultation,
- Adaptive-optics,
- Lightcurve
- Analysis

**Stellar occultations**

**Disk-resolved images**

Carry et al., Icarus 2010
Kaasalainen, IPI 2011
Carry et al., P&SS 2012
### Accuracy of KOALA

**Pre-flyby model**

**KOALA**

Carry et al. 2010

**vs. Rosetta**

Shape: 2 km RMS

Carry et al. 2012

**Accuracy**

Diameter $\sim 2\%$

Volume $\leq 15\%$
Accuracy of KOALA
On-going research…

1. Lightcurves & Stellar occultations
   - Interactions with amateur community
   - Now 200 convex shape models available
   - Size determination for 25%

2. Disk-resolved imaging
   - AO camera on VLT, Keck, Gemini
   - KOALA shape modeling
   - Working on ~30 objects

3. Adding data modes in KOALA
   - Mid-infrared (thermal) radiometry
   - Interferometry fringes
   - Radar echoes
   - Getting ready for massive inputs
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   - Getting ready for massive inputs
... up to 2020

- Spin
  - $10^5$ objects
  - Accretion epoch
  - YORP, Yarkovsky (non $\tilde{G}$)

- Shape & Size
  - $10^4 - 10^5$ objects
  - Size-freq. distribution
  - Dynamics & Collisions

- Surface properties
  - $10^4 - 10^5$ objects
  - Albedo, reflectance
  - Link with meteorites

- Density
  - $10^2 - 10^3$ objects
  - Composition
  - Internal structure
Summary

• **Asteroids are remnants from the early Solar System**
  ▶ Distribution of composition → initial conditions
  ▶ Evidences for planetary migration like many exoplanets

• **Asteroid composition remains elusive in many cases**
  ▶ Half of the classification lacks compositional interpretation
  ▶ Still a lot of observational constraints needed

• **Surface and physical properties mostly unknown**
  ▶ Albedo, thermal inertia, density → Composition
  ▶ Period, spin, shape → YORP & Yarkovsky