Linking NEAs to their main-belt source regions

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Stardust ITN: Opening Training School

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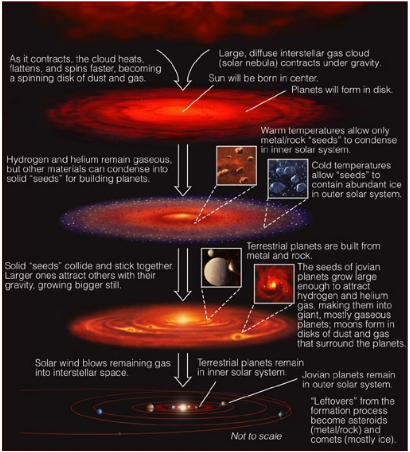
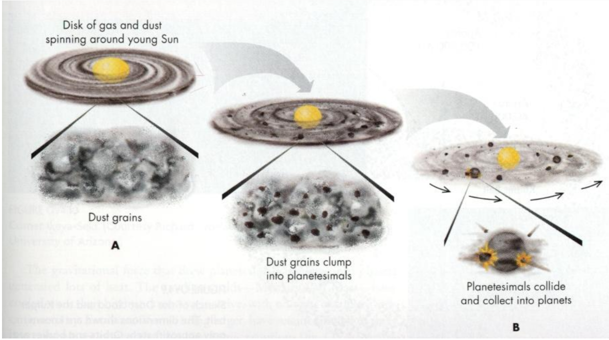
Formation of the Solar system: some basic facts



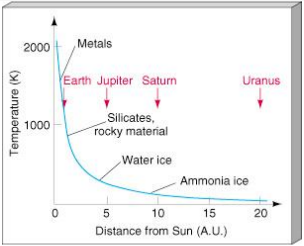
- The Solar Nebula Hypothesis: basis of modern theory of planet formation
- Main steps:
    - A rotating cloud of gas contracts, flattens and becomes warmer near its center ...
    - A thin disk of dust and gas is made around the forming Sun at the center ...
    - This disk gives birth to the Sun, planets, moons ...
    - BUT, also to asteroids and comets.

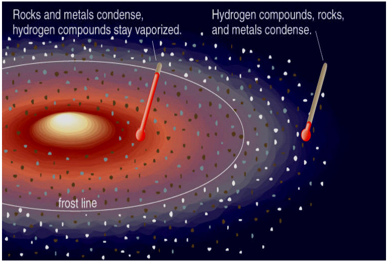
Asteroids: remnants from the Solar system formation



- Dust particles interact, sticking together to form larger and larger particles, i.e. planetesimals
- As planetesimals grow in size, their gravity attracts more gas and dust
- The collision between the planetesimals made even larger bodies, and eventually planets
- But some planetesimals were never incorporated into the planets

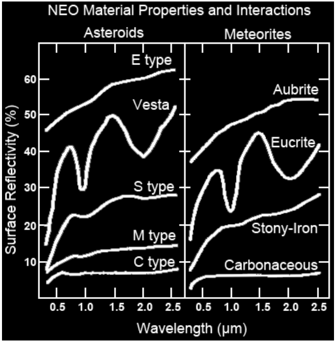
Leftover planetesimals from planet formation

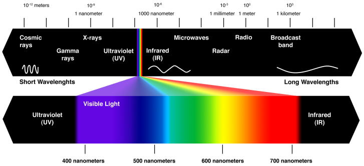




- Asteroids are planetesimals from the inner solar system, inside the frost line
- Comets are planetesimals from the outer solar system, beyond the frost line.
- But, even the asteroids vary widely in composition

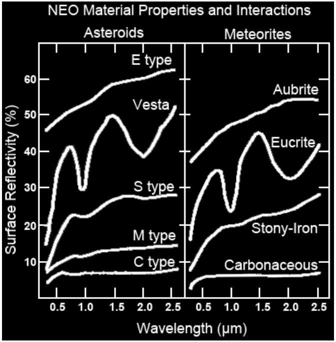
Spectra of an asteroid





- Albedo is the fraction of light that is reflected by a surface of an object.
- The sunlight reflected from the surfaces of asteroids, can be used to study composition of their surfaces.
- By determining which wavelengths of the spectrum were absorbed, and how strongly each band was absorbed relative to other bands, we can get an indication of what mixture of materials are on the asteroid's surface.

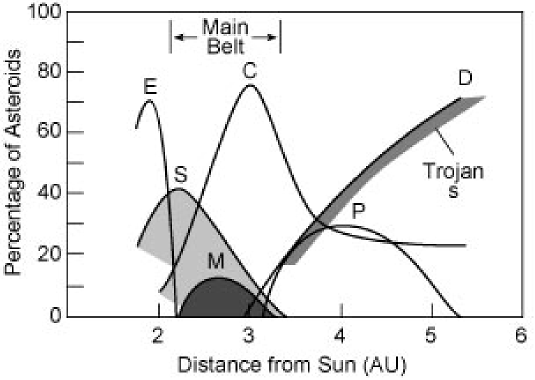
Spectra of an asteroid



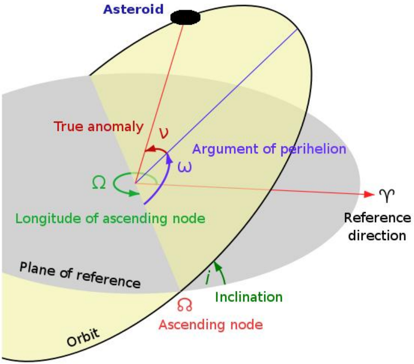
Several classification schemes exists:

- Tholen classification
- SMASS classification
- Bus-DeMeo classification (an extension of the SMASS taxonomy into the near-IR)
- Main complexes are:
  - C - dark carbonaceous objects; typical albedo $4-8\%$
  - S - silicaceous (stony) objects; typical albedo $15-25\%$
  - X - almost all other

Distribution of spectral classes in the main-belt

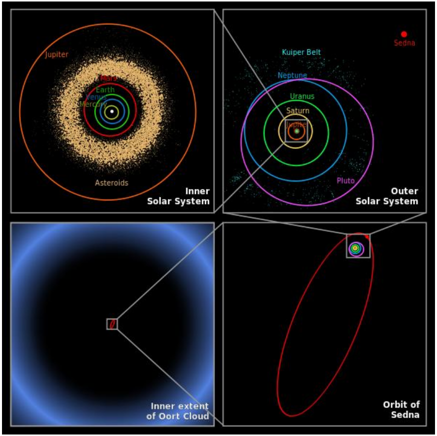


Orbital elements

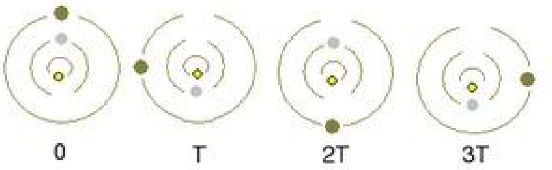


- semi-major axis: a
- eccentricity: e
- inclination: i
- longitude of ascending node: Ω
- argument of perihelion: ω

Small bodies: just about everywhere in the Solar System



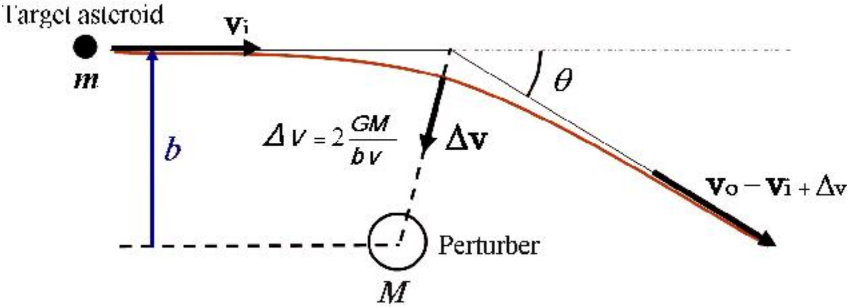
Gravitational phenomena: resonances



A resonance is a gravitational phenomenon that implies commensurability between two or more frequencies of the motion of the bodies that are orbiting around the same central body.

- mean motion resonances (e.g. $k_1 n + k_2 n_J \approx 0$)
- secular resonances (e.g. $k_1 g + k_2 g_S \approx 0$; $\nu_6 = g - g_6$)
- Kozai resonances ($g = s$)
- spin orbit resonances

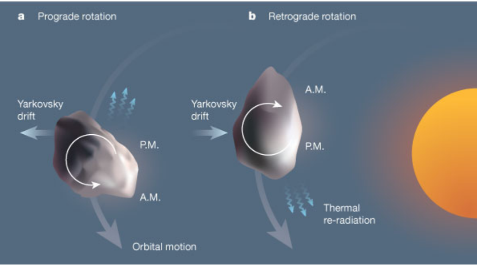
Gravitational phenomena: close encounters



Non-gravitational phenomena: Yarkovsky effect

- The Yarkovsky effect is the result of partial absorption of solar radiation at the surface of an asteroid and its anisotropic re-emission in the infrared band.
- Affects the orbital motion of asteroids smaller than about 30 kilometers in diameter
- For asteroids it scales as $1/D$, where D is the bodys diameter
- The resulting drift speed in the semi-major axis (da/dt) depends also on several other physical and dynamical parameters, such as thermal inertia, rotational period, spin obliquity, and orbital geometry

Non-gravitational phenomena: Yarkovsky effect

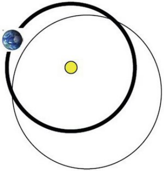


$$\left(\frac{da}{dt}\right) = 3.0 \times 10^{-5} \left(\frac{2.5 \text{ g cm}^{-3}}{\rho}\right) \left(\frac{5 \text{ km}}{D}\right) \left(\frac{\text{AU}}{\text{Myr}}\right)$$

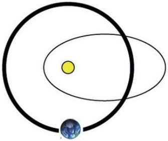
- Two components: the diurnal (rotational motion) and seasonal (orbital motion)
- The diurnal component: pro-grade rotation $\Rightarrow$ asteroid spiraling outward from the Sun; retrograde rotation $\Rightarrow$ asteroid spiraling inward towards the Sun
- The seasonal component: in most cases much smaller than diurnal
- Average drift due to the Yarkovsky effect: $1 - 5 \times 10^{-4}$ AU/Myr (for $D = 1$ km)

NEAs groups

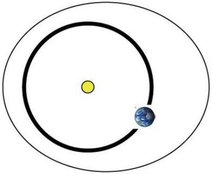
Apollo
Semimajor Axis ≥ 1.0 AU
Perihelion ≤ 1.02 AU
Earth Crossing



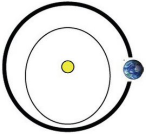
Aten
Semimajor Axis < 1.0 AU
Aphelion ≤ 1.0167 AU
Earth Crossing



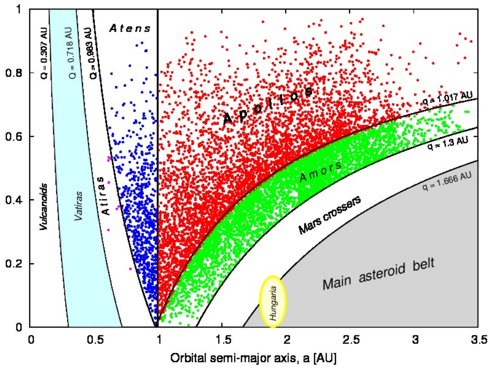
Amor
1.02 AU < Perihelion ≤ 1.3 AU



Inner Earth Objects (IEOs)
Aphelion < 0.983 AU
Always inside Earth's orbit
(aka Apohele)



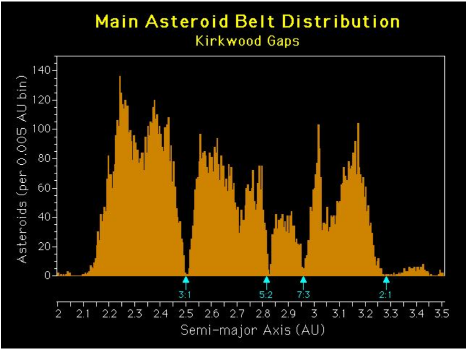
Type	Near-Earth Population
Apollo	62% of known asteroids
Aten	6% of known asteroids
Amor	32% of known asteroids
IEO	6 known asteroids



- Numerical integrations have shown that the typical lifetime of NEAs is about 10 Myr.
- They are eliminated by collision with the Sun, ejection from the Solar System, or collision with the planets.
- The real dynamic in the NEO region is the result of a complicated interplay between resonances and close encounters, therefore eminently chaotic.

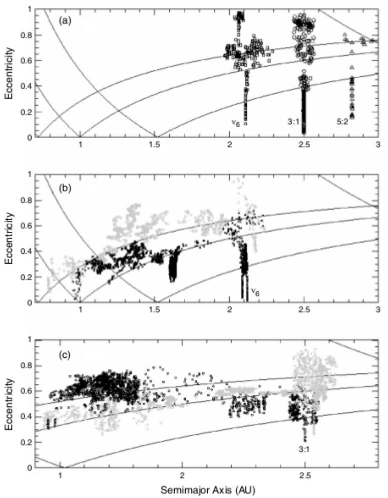
- The short lifetime of NEAs means that this population is not primordial, but it is kept in a sort of steady state by a constant supply of new objects from some source regions.
- It is a reasonable hypothesis that the origin of NEAs is related to the most prominent gaps (Kirkwood gaps) in the distribution of orbital semi-major axis in the main asteroid belt.
- Today, it is clear that the asteroid belt is able to efficiently supply most NEAs.
- An interplay among collisional processes, Yarkovsky force, may steadily bring new bodies into the gaps

Source regions and transport mechanisms



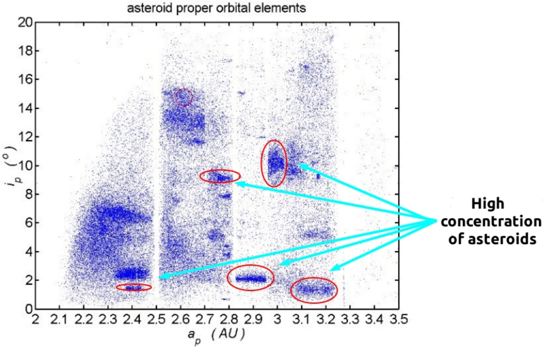
- ν_6 secular resonance with Saturn
- 3/1 mean motion resonance with Jupiter
- 5/2 mean motion resonance with Jupiter
- 2/1 mean motion resonance with Jupiter
- Diffusive Resonances

Transport mechanisms



- Many resonances are capable of transporting particles to Mars crossing, and often even Earth crossing, orbit.
- The gravitational attraction of a planet can then pull these particles out of the resonances, and subsequent close encounters modify the or bits of the extracted particles.

- Asteroid families are believed to be the products of the disruptions of a number of single parent bodies.
- Families are usually identified in the space of proper elements: the semi-major axis, eccentricity, and inclination.
- Objects belonging to the same family share certain orbital and spectral properties.



Asteroid families as a source of NEAs

- Some families are located just on the borders of some of the most powerful resonances.
- During the family forming events, many fragments are injected into these resonances.
- Larger families should have produced transient episodes of intense craterization of the terrestrial planets (asteroid showers) whose duration depended in each case upon the involved MMR, and on the number of fragments injected into it.
- Members launched close to a resonance (but not inside it) could be later transported into the resonance due to the Yarkovsky effect.

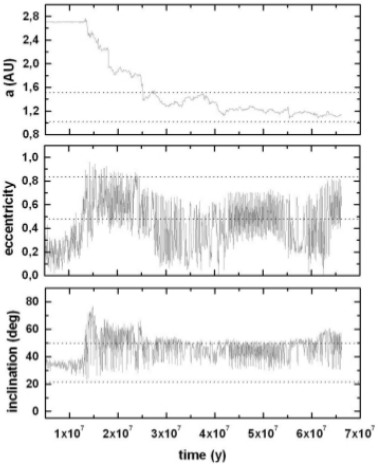
Linking NEAs with their origins

- Orbit of an asteroid, combined with physical properties, can give a good sense of where this object originated.
- Establishing transport routes from the main-belt to the near-Earth region
- Estimating probability of different scenarios
- Modeling dynamical evolution of specific object in the near-Earth regions
- Colecting all possible spectral and physical data

3200 Phaethon and the Pallas family

- Numerical simulations are carried out to explore the dynamical connection between the orbital neighborhoods of Pallas and Phaethon.
- Comparison of visible and near-infrared spectra of asteroids Phaethon and Pallas.
- Comparison of spectra of Phaethon with all the available visible spectra of B-type asteroids belonging to the Pallas family.
- Search for any correspondence between Phaethon and any B-type asteroid in the main belt

3200 Phaethon and the Pallas family



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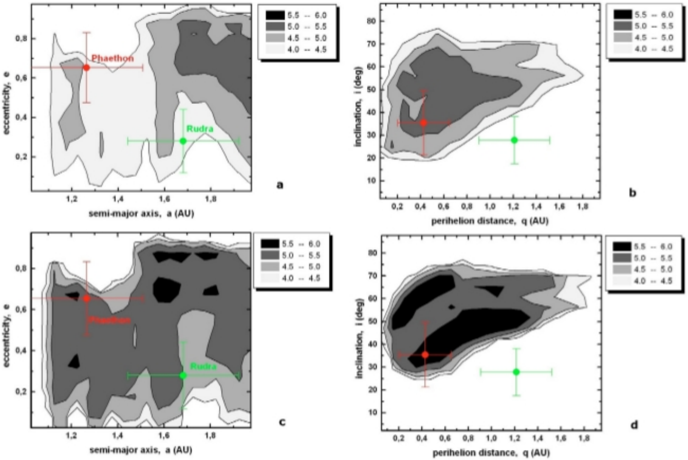

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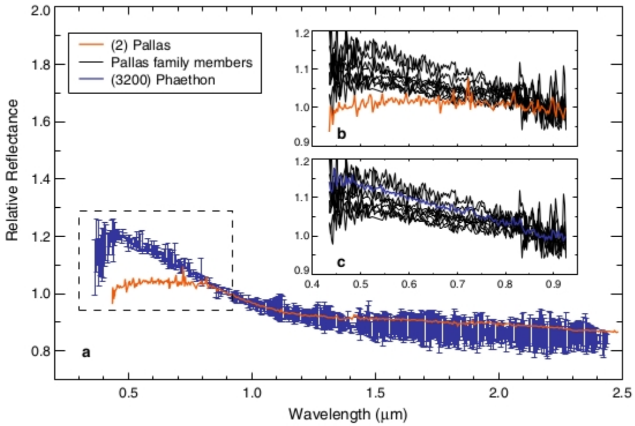

Conclusions

- Increased computational power ⇒ dynamical simulations in better resolution
- Improved observational data ⇒ e.g. better modeling of Yarkovsky effect, more asteroids to compare etc.
- In the recent years, advances in ground-based and mission work (e.g. SDSS, Pan-STARRS, WISE), as well as increases in computer power, open possibility to link a specific NEA to a potential source region in the main belt.
- A few links has been already established, but many more are expected to be settled in the coming years.