INVITED SPEAKERS

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Spectral analysis of the surface of Vesta in the wavelength range 2.5
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Properties of carbonaceous asteroid analogue materials: response to hypervelocity impacts

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Abstract

The on-going asteroid sample return missions, Hayabusa2 and OSIRIS-REx, are examining the surfaces of the km- and sub km-sized asteroids Ryugu and Bennu respectively. Results from the preliminary observation surveys of these missions reveal that Ryugu and Bennu have compositions that can be spectrally matched to those of CI or CM carbonaceous chondrite meteorites (Hamilton+ 2019; Kitazato+ 2019), and have a surface densely covered by boulders (Sugita+ 2019; Walsh+ 2019; DellaGiustina+2019). However, geomorphology of these boulders and their temperature response to the changing illumination conditions (day night cycles) indicate
that they could have thermo-mechanical properties that are not represented by meteorite samples that we receive on Earth (Sakatani+ TherMoPS III; Hamm+ TherMoPS III; DellaGiustina+ 2019). Ryugu and Bennu are spectroscopically and dynamically linked to the low albedo, low orbital inclination collisional families of the inner Main Belt (Bottke+2015, deLeon+2016, Pinilla-Alonso+2016), and therefore their materials could be representative of a large population of main belt asteroids.

Here we report on laboratory experimental campaign devoted to measure the thermo-mechanical properties of asteroid analogue materials, supposedly similar to those of Ryugu, Bennu, and of other low albedo inner main belt asteroids. In particular, we describe the response of these materials to impacts at several km/s. This allows us to shed light on questions like: what would be the granularity and the state of regolith produced by impacts on these materials? We aim to investigate the regolith properties produced by impacts and thermal cycles. How is regolith produced on those surfaces and which is the dominated processes between impacts and thermal phenomena?

Reference:

Massive Asteroid DataBase (MAD-Base) to reveal solar system’s origins

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Abstract

Here we describe the upgrade of a massive database that will host all the known physical properties of asteroids. Values of these physical properties do exist, but are currently diffused in the literature, as well as in several data archives (from space missions or research teams). We perform a deep and broad data mining in order to gather all possible physical data. Since for a large fraction of asteroids several values for a specific physical parameter exist, a critical evaluation of the values will be performed in terms of accuracy and data will be combined by appropriate weighing factors, to express the best values. We invite all the scientific community related to asteroid science to join this effort of collecting data. Laboratoire Lagrange hosts an infrastructure under update for this database: the Minor Body Physical Properties Catalogue (mp3c.oca.eu). MP3C, that is unique in the world and compliant with the Virtual Observatory of France and of the
EU, is ready to accept asteroid physical data. Such a database is the absolute tool for a scientific exploitation in asteroid science and beyond.

A great application is on asteroid families as, so far, not all families have been discovered. In particular, the members of the older ones are confused with the planetesimals, forming an “asteroid background” of unidentified origin. Looking for correlations of size and distance, the shapes of old families can be revealed. A new method developed at Laboratoire Lagrange has been successfully used (Delbo+2017, Bolin+2017, Delbo+2019), that is based on the asteroid physical properties (such as size, albedo and composition) which are used to separate the different families. Some of these primordial bodies, the leftovers from the planetary formation era, are still present in the asteroid Main Belt but currently are mixed with families of millions of newer generation asteroids. Planetesimals are the “holy grail” of planetary science, as researchers seek to locate the primordial materials in our Solar System and thus the primordial bodies which carry them.

Reference:

Surface composition of (162173) Ryugu as observed by Hayabusa2 mission

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Abstract

The JAXA asteroid sample return Hayabusa2 mission, launched on December 3, 2014, recently arrived to the primitive asteroid (162173) Ryugu after 3.5 years cruise (Watanabe et al. 2019, DOI: 10.1126/science.aav8032). On June 27, 2018 the spacecraft was set in its Home Position at 20 km from Ryugu, hovering the asteroid to start the initial mapping phase. From that time Hayabusa2 mission acquired a huge quantity of data at several distances.

The near-infrared spectrometer NIRS3 acquired reflectance spectra in the wavelength from 1.8 to 3.2 μm range operating in scanning mode (Kitazato et al. 2019, DOI:10.1126/science.aav7432). The spectral data show a weak positive spectral slope in the first part of the spectra and a clear weak narrow absorption band at 2.72 μm, detected across the whole observed surface. The absorption band
indicates the presence of OH-bearing minerals, associated to Mg-rich phyllosilicates (Kitazato et al. 2019, DOI: 10.1126/science.aav7432). Combining the spectrophotometric data obtained by ONC-T camera (Sugita et al. 2019, DOI: 10.1126/science.aaw0422) covering from 0.4 to 0.95 μm, the data obtained by VLT-ESO (Perna et al., 2017, AA599, L1) up to 2.2 μm and the NIRS3 data up to 3.2 μm, no meteoritic samples seem to have reflectance spectra to match perfectly those of the Ryugu’s surface obtained at the same wavelengths. The only possible similarity has been found with the spectra of thermally-metamorphosed CI chondrites and shocked CM chondrites.

The spectra analysis shows almost homogeneous surface with small variations. A detailed analysis has been conducted to study more in deep any possible small surface compositional variation and to support the landing and sampling sites selection (Yabuta et al. 2019 LPSC#2304). A multivariate statistical analysis has been carried out to characterize small spectral heterogeneities of the Ryugu surface composition and compared with morphological surface structures.

Acknowledgments: We thank the Hayabusa2 engineering teams for their efforts in making the mission successful and enhancing science operations, in particular T. Masuda, S. Yasuda, K. Matsushima, and T. Ohshima. We also thank H.
Murao, Y. Sakata, and K. Taguchi for the development of NIRS3.
Prospecting for the Solar System's original planetesimals

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Abstract

One of the main goals in understanding the planetary formation process is to know how the first building blocks of planets, the planetesimals, formed. Planetesimal formation theories are in disagreement on which physical processes grow planetesimals and on their initial size distribution (Johansen et al. 2015). Here, we take an observational approach to constrain the formation of planetesimals by separating asteroids that are fragments of collisional families from those that accreted in the protoplanetary disk. We use a systematic approach to search the inner Main Belt for previously unknown asteroid families. Our search identifies a >4 Gyr-old family in the inner Main Belt, one of the oldest known families. Its location reveals a zone in the inner Main Belt containing some of the original planetesimals (Delbo et al. 2017). All of the planetesimals are larger than 35 km suggesting that they had an initially shallow size distribution.
and formed large. In addition, we reveal another possible family, older than 2 Gyrs and located in the high-inclination Main Belt. This newly-discovered family consists family of mostly S-type asteroids and is located near several important resonances and sources of NEOs.

**Reference:**

Who is (6478) Gault? APO time-resolved visible to near-infrared photometry and spectroscopy of a newly active asteroid in the inner Main Belt

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Abstract

The high-inclination, inner Main Belt asteroid (6478) Gault has been observed to be active having undergone two separate activity-producing events since October 2018, more than 1 year before reaching perihelion (Smith et al. 2019, Jehin et al. 2019, Ye et al. 2019). We present optical and near-infrared observations of (6478) taken with the ARC 3.5 m telescope at Apache Point Observatory between January 8, 2019 and February 25, 2019. We obtained broadband optical and near-infrared colors and optical spectroscopy that suggest (6478) belongs to the C-complex making it a possible interloper in its dynamical association to the to the Phocaea asteroid family or that it may belong to the overlapping dark-albedo Tamara family (Novaković et al. 2017). Assuming albedo's typical for C-type asteroids, we determine that (6478) has a diameter of ~7 km. We obtained several lightcurves of (6478) each spanning hours. Most of the lightcurves show little variation on short
timescales possibly due to contamination by dust in the photometry measurements of the nucleus. Although, one lightcurve was obtained with exceptionally good image quality and shows sinusoidal variation with a peak-to-peak amplitude of ~0.2 mag over a time scale of ~1.5 hours. Time-series archival data of (6478) taken by the Canada France Hawaii Telescope in combination with the ARC 3.5 m data reveals (6478) to have a double-peaked rotation period of ~5 hours. This rotation period indicates that it may be approaching rotational instability if we assume typical C-type asteroid densities. We therefore conclude that the activity of (6478) is caused by escaping surface regolith that has become locally unstable due to rotational stress, although, we caution this statement with the fact that the rotation period of (6478) is significantly longer than the rotation period of other C-type asteroids with activity caused by rotational instability (Drahus et al. 2015, Sheppard & Trujillo 2015).

Reference:
Jehin, E. 2019, Central Bureau Electronic Telegrams, 4606
Nesvorny, D., Brož, M., & Carruba, V. 2015, Asteroids IV, 297
Smith, K., Denneau, L., Vincent, J.-B., & Weryk, R. 2019, 295 Central Bureau Electronic Telegrams, 4594

The environmental conditions created by an early formed Jupiter: A potential location for formation of our earliest dated solids?

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**Abstract**

Calcium-aluminum-rich inclusions, or CAIs, are highly refractory meteoritic materials and the most ancient known solids to form within the nascent circumstellar disk. Their formation marks the Solar System’s birth, providing a fiducial point for Solar System formation and evolution. However, in order to gain a comprehensive picture of early Solar System dynamics, it is critical to understand not only when these initial solid materials formed, but also where their formation was taking place. The canonical view of CAI-formation—based on chemical and radiogenic signatures—is that CAIs formed close to the young Sun and subsequently were transported to more distal areas, particularly where carbonaceous chondrite meteorites formed. However, if CAIs formed in the outer Solar
System, nearer the area of carbonaceous chondrite formation, the requisite dynamics of the protoplanetary disk would be very different from the canonical vision. Recent work has shown that the early Solar System was separated by the early formation of Jupiter, which occurred no later than 1 Myr following CAI-formation [1], and potentially earlier. Early formation of a gas giant would have significantly altered the conditions present in various parts of the nascent disk, and this could have created a local environment with both high temperatures and intense irradiation, fulfilling the most important known constraints on the CAI-formation environment [2, 3]. In this work, we explore if environmental conditions mandated for CAI-formation could have been created by the early formation of Jupiter.

We find that if an approximately 10 Earth-mass core of Jupiter formed rapidly via pebble accretion [4], the resulting temperatures at a distance of up to four Jupiter radii (JR) would be higher than the temperatures mandated by CAI mineralogy. Additionally, with the measured modern irradiation environment of Jupiter [5] (which would have likely been even stronger at Jupiter’s inception [6]), CAIs could have received the proton dose required to explain their Be-10 data in <10,000 years at a distance of 4 JR. This work demonstrates that early formation of a gas giant theoretically could have created the environmental conditions required for CAI-formation in the outer Solar System, and such potentialities
need to be taken into consideration as models of the early Solar System are refined.

**Reference:**
Cohesive strength between regolith grains and activity on main belt asteroids

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Abstract

Since the discovery of the first main belt object displaying cometary activity, 133P/(7968) Elst-Pizarro, observational campaigns have discovered activity on several other main belt asteroids. We are investigating rotational disruption as a possible origin for the dust ejection activity observed on a number of these asteroids, for which other dust production mechanisms were ruled out. The sizes of particles escaping these active asteroids range from µm to m-scales indicating a shedding of surface granular material. Due to the small sizes of these active asteroids (most are smaller than a few km in diameter), their surface gravity is so low that the cohesion between individual regolith grains plays an important role in the mass loss events. This fact has recently come to light upon the discovery of the asteroid (29075) 1950 DA, whose spin rate is so fast that only cohesive forces can prevent it from breaking up. Perturbations to the surface regolith layer on
such small asteroids could therefore trigger mass shedding due to landslides, a process intimately linked to the material and mechanical properties of the regolith.

We have started an investigation combining laboratory experiments and numerical simulations in order to determine if regolith structural failure on the surface of asteroids can be at the origin of observed activity and if surface activity can inform us on the presence of water ice in deeper layers of active asteroids. This investigation includes a series of laboratory measurements on regolith simulant grains of different sizes and mixtures of regolith with water ice grains. These include static and dynamic angles of repose, compression and shear strengths, as well as cohesion. The obtained measurements are used in numerical simulations studying the behavior of surface granular material on small rotating bodies such as active asteroids. We will present our first results on grain sizes ranging from 100 microns to 1 cm and the influence of water ice grains on our measurements, as well as preliminary implications for the internal composition of active asteroids.

Reference:


Main Belt collisional evolution and family formation

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Abstract

The Main Belt is considered a major laboratory for asteroid-asteroid collisions. Its size-frequency distribution N(>D) is complete down to approximately 10 km; with most objects having a known albedo. At sizes 2-3 km, the true slope has to be reconstructed by debiasing or inferred from pencil-beam surveys. Yet, these projectiles seem to be crucial for a long-term evolution, because they are so numerous (4 x 10^5) they affect a topography of practically all big (D > 100 km) asteroids. Statistical collisional models thus need not only the correct absolute numbers, but also appropriate scaling laws, parametric relations and removal rates, especially for small targets. Collisions above some threshold produce observable asteroid families.

While the number of observed families steadily increases (currently 140), a preliminary analysis is needed to determine their physical properties (e.g. parent body size, escape
velocity, mean albedo, approximate density) and sort them out. Collisional models then can be constrained either by the number of large catastrophic disruptions, or possibly by the number of recent cratering events, which did not have time to totally disperse by the Yarkovsky/YORP effect.

Recently, adaptive-optics observations of $D > 100$ km asteroids by the VLT/SPHERE/ZIMPOL instrument offered some insight into their topography and statistic of surface features. Indeed, suggested craters seem to be related to projectiles few km in diameter and serve as another constraint.

Clearly, one has to focus on the largest remnant, which requires a sophisticated smoothed-particle hydrodynamics (SPH) model of the impact event -- with high-resolution, self-gravity, rotation, but without merging of particles to resolve the shape. Moreover, if there is a substantial reaccumulation, the remnant exhibits oscillations which can be damped by friction or (end of) acoustic fluidisation.

**Reference:**

-
Dating the arrival of CC bodies in the inner Solar System

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Abstract

The asteroid belt provides fossilized constraints of the Solar System’s compositional and dynamic evolution. By combining nucleosynthetic isotopic anomalies and radiometric age constraints of asteroidal meteorites it has been recently shown that the asteroid belt samples bodies from two fundamentally distinct source reservoirs (the NC and the CC reservoirs [1,2]), which co-existed and remained spatially separated for several Ma [2,3]. This efficient and prolonged separation may be related to the formation of Jupiter [2,3], which not only acted as a barrier against material exchange between the NC and CC reservoirs [4], but can also account for the subsequent scattering of CC bodies from the outer into the inner Solar System [5].
Since the arrival of volatile-rich CC material in the inner Solar System is predicted by global dynamic models, and key for the habitability of the terrestrial planets, constraining the exact timing of this event is of prime importance. However, as of now, only indirect evidence [6], or broad limits have been deduced. Based on Mo isotope data it was suggested that the earliest time that mixing could have occurred is when the youngest meteorite parent body with a NC or CC signature formed, i.e., around 4 Ma after CAIs [3]. In contrast to the meteorite parent bodies, the Mo isotopic composition of Earth's mantle is between those of the NC and CC reservoirs, indicating substantial accretion of CC bodies to the growing Earth [7]. However, as Earth accreted over tens of Ma, this information places only an upper limit of ~50-100 Ma after CAIs for the scattering of CC bodies into the inner Solar System.

Here, we improve on this issue by investigating the Mo isotopic composition of Mars. Since Mars' accretion was completed within 10 Ma [8], the presence or absence of a CC isotopic signature in the martian mantle reveals whether the CC bodies arrived before or after 10 Ma. We find that – although distinct from Earth's mantle— the Mo isotope composition of martian meteorites is also intermediate between the NC and CC compositions. This limits the onset of the CC scattering into the inner Solar System to <10 Ma after CAIs. This timescale is consistent with the growth history of
Jupiter and the gas disk dissipation timescale, and suggests that volatile-rich outer Solar System materials contributed to the growth of the terrestrial planets during significant parts of their accretion.

Reference:
Chemical and Physical Evolution Pathways for the Many Types of Main Belt Asteroids

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Abstract

The main belt of asteroid is largely populated by mid-sized (~100-300 km) asteroids whose collisions produced the bulk of the fragments composing the belt and are at the source of the meteorites retrieved on Earth. The latter provide important constraints on the internal evolution followed by the diverse classes of asteroids. The most important drivers of internal evolution are the amount of 26Al accreted (i.e., relative
formation chronology), the original amount of volatiles, material properties (e.g. ratio of fines to clasts; porosity; whether it was lithified prior to alteration), and the prospect for these bodies to differentiate, at least partially.

A few large outliers qualify as protoplanets, or dwarf planet in the case of Ceres, with outstanding evolution involving advanced physical and/or chemical differentiation. We review in particular the state of understanding of Vesta’s and Ceres’ evolutions following the Dawn mission and the state of knowledge of 16 Psyche ahead of the Psyche mission. Furthermore, new shape and density data resulting of many large asteroids from the HARISSA Team (VLT/SPHERE) yield an unprecedented opportunity for comparative evolution among large water-rich asteroids.

We will review evolution pathways for the main classes of asteroids (C, S, M) found in the main belt and in particular the feedbacks between physical and chemical evolution. Key questions regard the extent of hydrothermal circulation and resulting chemical fractionation; whether hydrothermal circulation occurs as an aqueous fluid through a permeable but coherent lithified rock, or mud convection within an unlithified asteroid; heat sources and forms of heat transfer, in particular the role of impacts in driving long-term activity; sources and sinks of volatiles and elements involved in prebiotic chemistry; and the prospects for the long-term
preservation of habitable environments in the largest water-rich asteroids. Finally, we address possible outcomes in terms of observables for telescopic and spacecraft observations.

Part of this work is being carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract to NASA. Government sponsorship acknowledged.

Reference:
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Simulating Effects of Solar Wind on M-Type Asteroids by Irradiation of Troilite

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Abstract

Space weathering is one of the dominant processes modifying the surfaces of airless solar system objects. Extending our knowledge of space weathering mechanisms and effects to metallic surfaces is a necessary prerequisite to making accurate interpretations as we explore such a metallic surface for the first time [1]. In stony materials, a readily observable effect of space weathering is the reddening and darkening of surface spectra [2], which has been linked to reduction of iron-bearing minerals [3] by two mechanisms: energetic ions from the solar wind [4,9], and micrometeoroid impacts [5-9]. Though these mechanisms have not been studied on the primary minerals of iron meteorites – kamacite and taenite [10] – they have been studied on troilite [9], an accessory mineral found in both stony and iron meteorites.

Anticipating future work on kamacite and taenite, we aim to replicate and extend existing work on troilite. We first used the Tracking and Range of Ions in Matter (TRIM) [14] to
predict the trajectories and penetration depths of protons and alpha particles into troilite and kamacite at varying energy levels between 4 keV and 4 MeV. We then irradiated samples of troilite from the Canyon Diablo and Toluca meteorites (provided by ASU’s Center for Meteorite Studies) using the iBeam at ASU for high-energy (3 MeV) ions, and using the Solar Wind Chamber at the University of Virginia for low-energy (4 keV) ions. We used both protons and alpha particles, though not simultaneously. In each irradiation, we used an accelerated aging technique [12], using sufficient ion fluence and experiment time to simulate ~10^5 years exposure to solar wind at 1 AU, a duration shown by [9] to reproduce space weathering observed on near-Earth objects.

From both modeling and experimental results, we interpret that incident ions with keV energies more effectively produce the observed results of space weathering than ions with higher energies, for a given total energy delivered to the surface. Thus, we conclude that solar wind particles [13] will dominate ions at higher energies [14] for producing space weathering textures. For future simulations of space weathering employing accelerated aging, increasing the energy of the incident ions does not replicate space weathering damage, and therefore increasing the fluence of incident ions is necessary to provide an accurate simulation of geologic time. With these conclusions, we plan additional experiments to investigate space weathering of other minerals.
likely found on metallic asteroids, including kamacite and taenite.

Reference:
[1] Elkins-Tanton et al. (2014) LPSC XLV Abstract #1253
VIS-IR spectral analysis of mixtures made of ice, organic matter and opaque mineral in support of remote sensing observations from space missions

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Abstract

The Rosetta mission at comet 67P/Churyumov-Gerasimenko revealed a surface ubiquitously covered with organic-rich materials [1,2,3] mixed with water ice [4] and opaque phases [4,5].
[5,6,7]. Organics and water ice have been detected at local scale also on Ceres’ surface [8,9], mixed with widespread phyllosilicates, carbonates and low albedo materials [10]. Following these observations, our goal is now to understand the relative abundance, grain sizes and mixing modalities of these phases.

Here, we present reflectance spectra, in the range 0.4-4.2 µm, measured at the Cold Surface Spectroscopy laboratory at IPAG (Grenoble, France) by means of the SHINE spectro-gonio-radiometer [11]. By using pyrrhotite as a darkening agent and kerite as an analogue of cometary and asteroidal refractory organic matter, we experimentally produced binary (ice-pyrrhotite, ice-kerite, pyrrhotite-kerite) and ternary (ice-pyrrhotite-kerite) mixtures stabilized at 173 K.

Pyrrhotite and kerite powders of controlled sizes from 63 µm down to sub-µm grains have been used. These have been mixed with water ice particles of 67±31µm produced by means of the SPIPA-B setup [12], to prepare intimate (“salt and pepper”) and/or intra-particle (ice particles embedding refractory sub-µm grains) mixtures.

The obtained dataset enables us to characterize systematically the spectral response of a given mixture in terms of end-member abundances, grain size and mixing modality, in support of the interpretation of remote sensing observations from space missions.
In addition, the availability of optical constants for water ice, pyrrhotite and kerite allows us to compare the measured spectra with the output of widely used solutions of the radiative transfer equation in regoliths, like Hapke’s [13] and Shkuratov’s models [14]. The main results of this experimental activity will be presented and discussed in the context of recent Rosetta and Dawn findings.

**Reference:**


A record of Saturn’s final migration fossilized in the asteroid belt’s orbital structure

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Abstract

The modern asteroid belt is composed of over 100,000 small objects with orbits between those of Mars and Jupiter. In stark contrast to the neighboring inner terrestrial and outer gaseous systems of planets, the asteroid belt is characterized by an extreme low-density of material on dynamically excited orbits (DeMeo & Carry 2013). The Nice Model (Tsiganis et al. 2005) explains many peculiar qualities of the solar system (Morbidelli et al. 2005; Levison et al. 2008; Clement et al. 2018), including the belt’s excited state (O’Brien et al. 2007; Clement et al. 2019 a,b), by invoking an orbital instability
between the outer planets. Furthermore, a recent model (Clement et al. 2018, 2019) proposed that the asteroid belt’s low mass, Mars’ diminutive size, and the disparity between the inferred accretion timescales of Earth and Mars (Kleine et al. 2009; Dauphas & Pourmand 2011) could all be reconciled if the instability occurred within a few million years (Myr) of the dispersal of the solar system’s primordial nebular gas. However, all previous studies (O’Brien et al. 2007; Deienno et al. 2016, 2018; Clement et al. 2019) of the Nice Model’s effect on the belt’s structure drastically fail to reproduce the innermost asteroids’ orbital inclination distribution. Here, we show how the absence of asteroids with orbital shapes that precess between 24-28″/yr is a remnant of the final phase of Saturn’s orbital migration. As interactions with leftover debris caused Saturn to move away from Jupiter, its rate of orbital precession slowed to conserve angular momentum. When the two planets approached their modern separation, where Jupiter completes just short of five orbits for every two of Saturn’s, Jupiter’s eccentric forcing on Saturn became more rhythmic. We use numerical simulations to show that this process speeds Saturn’s precession back up, thereby altering the asteroid belt’s inclination structure. Thus, our work offers a self-consistent explanation for the lack of high inclination objects in the inner asteroid belt.

Reference:
DeMeo, F. E. & Carry, B. The taxonomic distribution of asteroids


A new framework for analysis of carbonaceous chondrite (and asteroid) spectra

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Abstract

Studies of the spectral reflectance properties of carbonaceous chondrites (CCs) indicate that, in contrast to widely held previous beliefs, the vast majority of them exhibit absorption bands in the 300-2500 nm range that can be attributed to specific components in the meteorites. Components that exhibit potentially diagnostic absorption bands include Fe3+-bearing phyllosilicates, Fe3+-Fe2+-bearing phyllosilicates, Fe2+-bearing phyllosilicates, Fe2+-bearing olivine, Fe2+-bearing pyroxene, Fe2+-bearing spinel (in calcium aluminum inclusions), glassy/amorphous Fe-bearing silicate, and magnetite. The presence or absence of absorption features due to these components can be related to specific types of CCs. In addition, these absorption features are indicative of parent body processes.

Based on this relationship between spectral features and CC mineralogy, we have found that there are three (or four) CC “clusters” that are related spectroscopically, mineralogically,
and petrologically: (1) those that have undergone aqueous alteration and exhibit absorption features due to Fe$^{3+}$±Fe$^{2+}$-bearing phyllosilicates and/or magnetite (CI1, CM1-2; aqueously altered and thermally metamorphosed CCs (ATCCs)); (2) those that have undergone some degree of thermal metamorphism and exhibit absorption features due to some combination of pyroxene, olivine and/or CAIs (CV, CK, CH, CB, some CO), (3) those that exhibit absorption features consistent with glassy Fe-bearing materials (some COs and CRs); (4) and those that exhibit very weak or non-existent absorption bands (Tagish Lake, some CI1s, possibly CRs).

It appears that characteristic absorption bands are resistant to complete obliteration by processes that may occur on CC asteroidal parent bodies. The strongest evidence of this is the identification of asteroids (Cgh) that exhibit absorption bands fully consistent with CM2 meteorites.

Reference:
IR Spectroscopy of NH4-phyllosilicates mixtures and Ceres average composition

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Abstract

The surface composition of (1) Ceres has been revealed with great detail by VIR spectrometer high resolution observations [1] on board Dawn spacecraft [2]. Spectroscopic observations in the infrared range 1-5 micron have showed an average surface composition consisting of a mixture of Mg-phyllosilicate, (Mg,Ca)-carbonate, a dark absorbing phase and NH4-phyllosilicates [3], and bright areas locally composed by mixtures of Na-carbonates, phyllosilicates, a dark phase and ammonium compounds [4]. The reproduction in laboratory of such mineral mixtures is thus of interest in order to better constraint and interpret remote-sensing observations. In this work we focus on the preparation and IR spectroscopic measurements in laboratory of mineral mixtures consisting of various types of NH4-phyllosilicates with serpentine-
antigorite, magnetite and dolomite. Among all mixtures, only the ammoniated phase were changed, while the other three endmembers were kept fixed.

Seven different NH4-phyllosilicates have been used for the mixtures; phyllosilicates have been ammoniated in the laboratory starting from natural samples [5].

Five physical mixtures have been prepared using the three common endmembers (antigorite, magnetite and serpentine) and varying for each the NH4-phase among: two NH4-nontronites (NAu1 and NAu2), NH4-montmorillonite (SCa3), NH4- Hectorite (SHCa1), NH4-illite-smectite (ISCz1). These five mixtures have been measured at room P-T conditions with the ASD FieldSpec 4 HiRes (0.35-2.5 micron) and the SPIM spectrometer (1-5 micron) at INAF-IAPS [6]. Two other mixtures have been simulated by mixing the singularly measured common endmembers with two NH4-saponites (Sap-Bar and Sap-Baj). In particular in these two cases the NH4-saponites were previously measured alone in the 1-5 micron range with SPIM coupled with an environmental P-T chamber, in high vacuum and at high temperature (T>200°C).

A very good matching with Ceres average spectrum results from the mixture containing the NH4-saponite Sap-Bar heated at T=250°C in high vacuum.
Reference:
Ceres mineralogy as evidence of a global ocean

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Abstract

Ceres shows mineralogy and geology dominated by the action of water and other volatile ices mixed with rocks. The surface displays clearly the products of aqueous alteration and ice on the surface and subsurface. The recent chemical and physical measurements obtained by the Dawn mission permitted the identification of minerals resulting from the long term reactions between liquid water and rock. The surface is an assemblage of clays, carbonates, ice and organic material in different proportions, indicating a past history of liquid water. Moreover, Ceres shows clear sign of “recent” hydrothermal activity. The presence of ammonia in phyllosilicates and salts indicates the accretion of volatiles, such as ammonia in the original material from which Ceres formed, suggesting a cold formation environment. Moreover, the presence of organic species on Ceres, mixed with minerals formed by water alteration and hydrothermal processes, suggest a favourable environment for the developing of molecules precursor of biological molecules.
Ceres is an example of a relict ocean world. Here we describe the mineralogical evidences and the implications that hold for the broader solar system.

Reference:

-
V-Shape Detection Efficiency

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Abstract

Following the break up of a parent body, asteroid family member spread in orbital semi major axis with a rate inversely proportional to their diameter. This size dependent semi major axis drift causes family members to form structures in the semi major axis vs inverse diameter plane that have the shape of the letter V. The V-shape method consists in finding the borders of such V shapes of unknown center and opening. To date, there are two border search techniques used. Although both are based on searching for differences in the number density of objects inside and outside a nominal V and scan the space searching for the center and opening of the V that maximize said density contrast, the techniques differ from how the inner and outer edges of the V's are defined. The first defines that the density should largely change from the region within $K^*|a-ac|$ and $(K-dK)^*|a-ac|$ to that within $K^*|a-ac|$ and $(K+dK)^*|a-ac|$, where $K$ and $ac$ are the slope and center of the nominal V, with $dK$ a delta in the slope. The
second method search for large density changes from the region within $K^*|a-ac|$ and $K^*(|a-ac| + aw)$ to that within $K^*|a-ac|$ and $K^*(|a-ac| - aw)$, where aw represents the width of the nominal V. Although successfully used to find and characterize some very old families in the main asteroid belt, the V-shape searching method is very sensitive to how dK or aw are defined. Also, it is not clear how reliable a blind search of V-shapes would be depending on age and on the ratio from number density of the family members over background components. In this work, we created and evolved large number synthetic asteroid families over billions of years. Therefore, knowing precisely the age and center for each of our families at any given time, we can calibrate their nominal slopes. Thus, by assuming different levels of ratio of the family and background asteroids, and varying both dK and aw, we aim to derive a detection efficiency map for the V-shape method and determine how reliable the results can be based on signal to noise levels. Ultimately this will allow for an understanding of which size and age family this technique is best suited for and which are likely not detectable.

Reference:
N/A
Observing the planetesimals size distribution amongst main belt asteroids

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Abstract

The mechanism by which dust accretes into planetesimals is an important subject of debate in the planetary science community (1,2). Fundamental parameters, such as their original size frequency distribution of planetesimals are unknown (2). This problem is typically approached theoretically. Here we use astronomical data to identify the leftover planetesimals amongst all other asteroids, thereby constraining planetesimal formation processes. Our search is based on separating planetesimal survivors from families of asteroids generated by collisions all along the history of the Solar System.

If we could identify all collisional families and “clean” the Main Belt from their members, we would be left out with the
survivors of the original asteroids, the planetesimals. Unfortunately, current asteroid family catalogues are not suitable for this cleaning. They are conservative and only a quarter of known asteroids is associated with ~110 distinct asteroid families (3).

Thus, we have developed a more general method (4,5) to identify asteroids that are collisional fragments and applied it to the population of asteroids of the inner part of the Main Belt (population of asteroids with orbital semimajor axis between 2.1 and 2.5 au).

We discovered three very old asteroid families that escaped detection with classical families identification method (5,6). We report about our “cleaning” operation in the inner Main Belt and about the resulting planetesimal cumulative size distribution (5,6). This becomes shallow for sizes smaller than about 100 km and shows a lack of 30 km or smaller planetesimals, supporting previous works indicating that asteroids were born big (7,8,9).

This research is supported by the grants ORIGINS and IDEX-JEDI of the French Agence Nationale de la Recherche.

Reference:


Main Belt Asteroid Composition from Remote Observations

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Abstract

There are numerous methods to deduce asteroid compositions from remote observations, including spectroscopic, photometric, polarimetric measurements and from estimates of densities and surface albedos. In this talk I will summarize how each observational technique is useful in understanding surface compositions. I will review the taxonomic classes that separate asteroids into distinct spectral groups and summarize our current understanding of how those classes translate to composition. I will briefly review modeling techniques used to determine mineralogy. Asteroid compositions can be set from the time of their initial formation, but can be affected by processes happening throughout the body’s history such as heating, aqueous alteration, and exposure to energetic particles. Comparing remote observations with meteorite measurements or with “ground truth” from mission data including sample return also help to increase our confidence in interpreting composition.
Large observational surveys of the main belt allow us to explore how these asteroid compositions are orbitally distributed. I will review the distribution of asteroids throughout the main belt and discuss implications for their formation and evolution.

Reference:
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Dynamical and Collisional Evolution of the Inner Asteroid Belt

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Abstract

The six major families in the Inner Main Belt (IMB), Flora, Vesta, Nysa, Polana, Eulalia and Massalia, are surrounded in proper element space by halos of asteroids that probably originate from the same group of families. However, because of the overlap of these families and their halos in proper element space, use of the Hierarchical Clustering Method (Zappala et al., 1990) to assign halo asteroids to a particular family is difficult or impossible. However, if we do not attempt to assign halo asteroids to a particular family, then it is possible to extend the HCM to encompass the family asteroids and their surrounding halos and thus to identify a third group of asteroids: the non-halo asteroids (Dermott et al., 2018). One method of achieving this extension is to increase $d_{cut}$,
the clustering criterion, to the extent that one large cluster is of sufficient size to just encompass all of the IMB major families and their halos. At present, the separate families are defined by choosing limits on \( d_{\text{cut}} \) that avoid overlap or chaining, but these modest limits are arbitrary and have no particular dynamical significance. More importantly, these limits appear to capture only about half the likely family members. Here, we discuss several new methods of choosing \( d_{\text{cut}} \) based on (a) the differences of the observed size-frequency distributions of the family, halo and non-halo asteroids and (b) the observations that the mean proper eccentricities and mean proper inclinations of the family, halo and non-halo asteroids are correlated with their sizes. The non-halo asteroids in the IMB defined by these methods are shown to derive from old ghost families that now display a distinct lack of small asteroids. Having defined the three groups of asteroids, we are able to discuss the orbital evolution of these asteroids and to analyze observations of their interactions with Martian 2-body and 3-body resonances. Our results imply that we must seek explanations for the differing characteristics of the various meteorites and near-Earth asteroids originating from the IMB in the evolutionary histories of a small number of large, precursor bodies. They also reveal that the majority of the asteroids in the IMB are not part of an equilibrium, collisional cascade of the type described by Dohnanyi (1969).
Reference:


CAIs rich asteroids, from the main-belt to the Near-Earth space

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Abstract

When observed in polarimetry all asteroids possess similar characteristics. One of these is an inversion angle (when the polarization suddenly rotate by 90°) around a phase angle around 20°. However, Cellino et al. (2006) found that a peculiar asteroid (234) Barbara possess an usually large inversion angle around 30°. Later on, several asteroids have been found to share the same polarimetric properties. They have been collectively called Barbarians asteroids as a reference to Barbara.

A spectroscopic survey of the Barbarians revealed that they all belong to the unique rare L-type in the Bus-DeMeo near infrared inclusive taxonomy classification. L-types have been linked to primitive asteroids containing an unusually high fraction (up to 30%) of Calcium Aluminium Inclusions (CAIs) (Sunshine et al. 2008; Devogele et al. 2018). The CAIs are the most primitive material ever found in the Solar System, they are the first elements to condense from the proto-solar
nebula and are commonly used to define the age zero of the Solar System. However, such a high fraction of CAIs has never been found in any meteorite present on Earth where the highest fraction ever found is not higher than 13%.

Recently, we found the first confirmed Barbarian asteroid in the Near Earth asteroid space. This object possess the highest inversion angle ever observed with 33° of phase angle. The VISIR spectrum is also compatible with a L-type spectrum. Near-Earth asteroids are the direct feeding source of the meteorite collection on Earth. This finding raised even more the question of why do we not observed CAIs rich meteorite on Earth. Is 2009 DM1 an exception in the NEOs space or are they still to be found?

Model of the spectrum using laboratory spectra, suggest a composition identical to CV3 meteorites with higher fraction of CAIs. We also compared the spectrum with other known main-belt Barbarian asteroids and found that the spectrum is identical to the (387) Aquitania. The rarity of L-type in the MBAs, their peculiar unique polarimetric and spectroscopic properties are a unique opportunity to provide a direct link between asteroids observed in the MBA and the NEA space.

2009 DM1 also presents an unique opportunity to observe a primitive CV3 meteorite analog in space. It is then a very high priority target for space-probe exploration.
Reference:
Distribution of spin axes of main-belt asteroids

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Abstract

Rotation periods, spin-axis directions, and coarse shapes are basic physical properties of asteroids that can be reconstructed from disk-integrated time-resolved photometry. By building up a large sample of asteroid models with known physical properties, we can reveal the distribution of these properties across the main belt, which is important for understanding the evolution of asteroid population. In particular, the distribution of spins is affected by collisions and by dynamical mechanisms like spin-orbital interactions or YORP effect. The current sample of asteroids with known rotation state consists of thousands of models. Although this is still only a small fraction of the known population, we can already see clear trends in the spin-axis distribution with respect to the asteroid size, proximity to mean-motion resonances, family membership, etc. The aim of our talk is to
present current results of the shape/spin modelling, show the most prominent trends and correlations in the distribution of asteroid spins, and discuss some prospects for the future.

Reference:
none
Constraints and models for the composition and formation of Psyche

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Abstract

The main belt asteroid (16) Psyche is thought to be metallic, based on thermal inertia, radar reflectance, and other observations. Here we will summarize existing observational data on Psyche, and then compare them to meteorite types. Researchers have suggested analogs for Psyche include irons, stony irons (pallasites and mesosiderites), and some classes of chondrites.

For comparisons to meteorites to be meaningful, however, they need to be filtered through plausible formation hypotheses for Psyche as well as discussions of the extrapolation from hand-sample-sized meteorites to the 200-km diameter Psyche. Some argue Psyche is a stripped planetesimal core, while others suggest it is a droplet or
brecciated metallic or metallic-silicate fragment from a bigger disrupted core. It is also conceivable that it is an unmelted highly reduced remnant from the innermost solar system. In all of these cases, the possible distributions of porosity, fracturing, and compositional heterogeneity need to be calculated to arrive at both Psyche’s bulk density and surface composition.

Finally, we will discuss the expected mission observations that will help decide the nature of the asteroid when the spacecraft arrives in 2026. These observations include magnetic field, nickel content, scale of silicate/metal mixing, structure and density, and whether silicates are achondritic or chondritic.

**Reference:**
Request from author.
Meso to nanoscale approach of water-rock interactions in carbonaceous chondrites using X-ray diffraction computed tomography

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Abstract

Many studies have dealt with the patterns of water circulation and water-rock interactions in C- and H-rich small bodies \(^{(1)}\), from which carbonaceous chondrites are representative
samples. Several questions relative to this thematic can be addressed by mineralogical studies: what are the water-bearing phases in bodies that may have contributed significantly to the budget of water on Earth (2)? This is one of the important questions addressed by samples return missions to primitive asteroids (3). The nature of the water carriers has profound consequences on the stability of water upon transport and partitioning upon impact, hence the importance of studying the mineralogy of hydrated phases. What are the stability conditions of these phases? Understanding which types of small rocky bodies may have preserved their water requires understanding the conditions yielding the formation of stable hydrated phases, which can be addressed through a description of mineralogical assemblages and distribution of secondary phases. Mineralogical variations occur at various scales in carbonaceous chondrites, down to the nanometer scale, requiring the use of a combination of techniques.

Here, we focus on the mineralogy of serpentines, one of the main carriers of water in carbonaceous chondrites, and associated phases in CM chondrites. We used a combination of nanometer scale techniques (nano-focused X-ray diffraction computed tomography (XRD-CT), Focused Ion Beam, TEM, XANES coupled with spectromicroscopy) and a mesoscale approach (micro-focused XRD-CT coupled with absorption CT) on meteorites presenting various intensities of interaction
with liquid water in their parent bodies. Combining nanoscale techniques, we propose structural parameters for chondritic serpentines, which compositions depart from those of terrestrial serpentines (4). Such data are necessary to evaluate the mixing properties in the Fe-Mg-Al-Si system, a prerequisite for modelling the conditions of formation of serpentines in asteroidal environments. From the mesoscale data, we can evaluate the mineralogical homogeneity of secondary assemblages, an interesting proxy for the pattern of circulation of water. Second, these data allow us to describe the evolution of the mineralogy of serpentines with hydration, and to evaluate its variations from an altered chondritic object to the other (CAI / chondrules) (5). Finally, a wealth of information is gained by identifying and mapping the distribution of nanophases (serpentine with various interlayer stacking distances comprised between those of lizardite in one hand, amesite and cronstedtite in the other hand, tochilinite, and small amounts of other phases, including bassanite and hydrotalcite) in millimeter size fragments of meteorites through a non-destructive approach.

Reference:


(5) A. Elmaleh, Wright, J.P., Baptiste, B. et al., in prep.
Reflectance spectroscopy of ammonium-bearing phyllosilicates

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Abstract

Ammonium-bearing minerals on the surface of (1)Ceres have been suggested by [1], using ground based observations and successively detected by the VIR spectrometer [2], on-board the Dawn spacecraft [3]. In this case, spectroscopic observations in the range of 1-5 μm have showed an average composition consisting of a mixture of Mg-phyllosilicate, (Mg,Ca)-carbonate, a dark absorbing phase, and NH4+-phyllosilicates [4], identified by a clear signature at about 3.07 micron. Nevertheless, the specific phyllosilicates bearing ammonium were not fully constrained by the observations, also due to the limited availability of NH4+-phyllosilicates spectra in the literature. IR reflectance studies of ammonium-bearing minerals and rocks (e.g. [5, 6, 7, 8,9]) show spectral features related to ammonium and other nitrogen complexes at 1.56 μm, 2.05 μm, 2.12 μm, 3.06 μm, 3.25 μm, 3.55 μm, 4.2
μm, 5.7 μm and 7 μm. In this study, we describe the laboratory production and IR spectroscopic measurements of a suite of ten NH4-phyllosilicates, starting from the corresponding NH4-free minerals. For each mineral, we prepared three types of powder samples: raw, ammoniated, and leached. All samples have been spectrally characterized by means of visible/infrared spectroscopy in the INAF-IAPS laboratories with the FieldSpec Pro in the 0.35-2.5 μm range, and with the FT-IR, using a Vertex 80 spectrometer operating in the range of 2 to 14 μm. The samples were also measured with the SPectral IMager, an imaging spectrometer operating in the spectral range 0.2 – 5.1 μm, which is a replica of the VIR spectrometer on-board Dawn spacecraft. This work demonstrates that different phyllosilicates respond differently to the treatment with ammonia. Only the expandable phyllosilicates can incorporate the ammonium ion within their structure by contact with ammonium-rich fluids at low temperature and pressure [10]. Phyllosilicates of magmatic or metamorphic origin, such as biotite and serpentine, do not show spectral variations due to the presence of ammonium. The presence in nature of micas (e.g. biotite and muscovite) with ammonium does not exclude that these can be enriched with ammonium under conditions of temperature and pressure higher than those used in this experiment [11, 12, 13]. The obtained results can be used to better constrain the
ammonium carrying species present on Ceres and allow to speculate on a scenario for its thermal evolution.

Reference:
Thermal convection in small bodies: some applications

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Abstract

Thermal convection is an important physical mechanism that affects the geophysical history of some bodies of the Solar System. In this work we focused in particular on two asteroids: Ceres - characterized by a huge abundance of water ice both in the interiors and surface/subsurface layers (es.[1,2,3,4]), and Psyche - the most massive metallic M-type asteroid.

For this purpose we developed a 2-D Finite-Element-Method (FEM) numerical code, which solves the Navier-Stokes equations coupled with the heat equation, in Boussineq approximation.

Our numerical results provide physical constraints for the onset of the thermal convection. In particular, for Ceres we tested the possibility to have cryovolcanism and dome formations, induced by the thermal stress; for Psyche, instead, we verified the conditions to have a core dynamo and consequently the timescale of a magnetic field.
Reference:


Spectral diversity on Themis family members: heterogeneity in the parent body or space weathering effects?

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**Abstract**

The Themis family is one of the most statistically reliable families in the asteroid belt. Consisting in more than 5000 members according to Nesvorny et al. (2012), it represents a reservoir of water ice in the outer main belt. Some main belt comets belong to, or originate from, the Themis family. Moreover on its main body, (24) Themis, exposed water ice has been detected over a significant fraction of its surface (Campins et al. 2010, Rivkin and Emery 2010). This is puzzling because of the instability for exposed water ice at Themis’s heliocentric distance (3.2 AU). Beside the exobiological implication related to the presence of hydrated materials and exposed water ice, Themis is also a natural laboratory to study the space weathering effects, not yet fully understood for the dark and carbonaceous chondrite like materials. In fact, within the relatively old Themis family (about 2.5 Gyr), there is a young sub-family, called Beagle, of estimated age lower than 10 Myr.
The analysis of visible and near infrared spectra published in the literature on a sample of 78 Themis members and 31 Beagle members (Fornasier et al., 2016) reveal that: i) the Themis family members have a higher spectral diversity and a lower mean albedo value compared to the younger asteroids of the Beagle family; ii) Beagle members are clustered in the spectral slope space, and are brighter and bluer compared to Themis member; iii) few Themis members show absorption bands related to the presence of hydrated minerals; iv) the meteorite analogues of both Themis and Beagle members are carbonaceous chondrites having experienced different degrees of aqueous alteration.

The presence of aqueous altered materials on the asteroids surfaces and the meteorite spectral matches indicate that the parent body of the Themis family experienced mild thermal metamorphism in the past. The observed spectral diversity between Beagle and Themis members may be an effect of space weathering processes. If so, these processes act on the primordial surfaces of Themis asteroids in a similar way than on silicate rich bodies, that is producing darkening and reddening. However there a relatively high spectral variegation inside Themis members, with some of them having similar albedo and spectral slope values to the younger Beagle members. Thus the spectral diversity may be due not only to space weathering effects, but possibly also to compositional heterogeneities with depth in the parent body.
Reference:
Nesvorny et al., 2012, EAR-a-VARGBDET-5-NESVORNYFAM-v2.0. NASA Planetary Data System.

Campins et al., 2010, Nature 464, 1320

Rivkin & Emery, 2010, 464, 1322

Fornasier et al., 2016, Icarus 269, 1
Paleomagnetic records of outer solar system magnetic fields

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Abstract

Magnetic fields in the solar nebula may have been critical for sustaining turbulence in the nebular gas, which is a requirement for leading hypotheses of planetesimal accretion [1]. At the same time, gradients of magnetic fields in the solar nebula, although far from being fully understood, is a potential method for distinguishing the formation locations or contexts of accreted materials [2].

Paleomagnetic measurements on meteoritic inclusions such as chondrules can infer the strength of magnetic fields at the time of chondrule formation, potentially placing constraints on the dynamics of nebular gas and the extent of radial mixing. Measurements on the LL ordinary chondrite Semarkona suggests that its chondrules formed in a ~50 μT magnetic field 2 million years (My) after calcium aluminum-
rich inclusions (CAIs) [3]. Meanwhile, a subsequent study of angrites suggests that ambient magnetic fields had decayed to \( \leq 0.6 \, \mu \text{T} \), implying at least local dissipation of gas by \(~3.8 \, \text{My} \) after CAIs [4].

CR chondrites are a group of meteorites with distinct elemental and isotopics compositions compared to ordinary chondrites and have therefore been hypothesized to have an outer solar system origin [5]. Meanwhile, chondrules extracted from CR chondrites have been dated to \(~3.7 \, \text{My} \) after CAIs [6]. Paleomagnetic estimates of nebular magnetic field based on CR chondrules may therefore expand our understanding of nebular magnetism to the outer solar system and to the final stages of nebular evolution.

We present paleomagnetic experiments on 15 individual chondrule samples extracted from CR chondrites LAP 02342 and GRA 95229. The magnetization directions of eight subsamples from five LAP 02342 chondrules show strong scatter, suggesting formation in a magnetic field of \( \leq 15 \, \mu \text{T} \) based on acquisition experiments of a laboratory anhysteretic remanent magnetization (ARM). Meanwhile, similar measurements of seven igneous sulfide rims [7,8] from a single large chondrule of the GRA 95229 meteorite, performed with the high-resolution quantum diamond microscope (QDM; [9]), suggest formation in a \( \leq 30 \, \mu \text{T} \) field. Together, these results indicate that CR chondrules formed in a weaker
magnetic field compared to those of LL ordinary chondrites, consistent with an origin at larger orbital radii.

**Reference:**


Accurate and quantitative modeling of the formation of terrestrial planet and the origin of Earth's water

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Abstract

It is widely accepted that collisions among planetary embryos is the key process in the formation of terrestrial planets and transport of water and volatiles to their accretion zones. Unfortunately, due to computational limitations, these collisions are often treated in a rudimentary way where impacts are considered to be perfectly inelastic and water to be fully transferred from one object to the other. This perfect-merging assumption has profound effects on the mass and composition of final planetary bodies as it grossly overestimates their masses and water contents. It also entirely neglects collisional-loss of volatiles and draws an unrealistic connection between these properties and the chemical structure of the protoplanetary disk. We have developed a comprehensive methodology and a self-consistent approach to modeling the formation of terrestrial
planets and origin of Earth’s water where we simulate collisions directly, and for the first time, consider the loss of water due to the heat of the impact, mass-removal during collisions, and ice-sublimation during orbital evolution of bodies. Using a combination of SPH and N-body codes, we model the collisions and growth of embryos to planetary bodies, and account for the loss of water and volatiles during impacts. Results of our simulations indicate that 1) traditional N-body modeling of terrestrial planet formation overestimates the amount of the mass and water contents of the final planets by over 60% implying that 2) not only is the amount of water they suggest, far from being realistic, 3) small planets such as Mars can also form in these simulations when collisions are treated properly. Results also suggest that because of the loss of water during impacts, the initial water contents of planetesimals and planetary embryos in the protoplanetary disk have to be higher than their traditional values in order for the water contents of the final planets to be comparable with that of Earth. We will discuss details of our methodology and present its results and implications.

Reference:
A survey of collision outcomes during planet formation: water transport and loss, Maindl et al, EPSC 2018, id.EPSC2018-995

Water transport and water loss by collisions during planet formation, Maindl et al, EPSC 2017, id. EPSC2017-578

Accurate Treatment of Collision and Water-Delivery in Models of Terrestrial Planet Formation, Haghighipour et al, LPSC, 2017, id.2030
The original mass of the asteroid belt: dynamical excitation mechanisms of a low-mass population and depletion mechanisms for a large-mass population

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Abstract

The current total mass in the asteroid belt is estimated at less than one one-thousandth of Earth's mass. Yet asteroids' orbits show a large spread in orbital eccentricities and inclinations. The origin of the asteroid belt remains debated. In one school of thought the asteroid belt region was born high-mass with a few Earth masses of solid material then was depleted and dynamically excited by different mechanisms. This lies at the foundation of the Grand-Tack and Early Instability models for the inner Solar System's early evolution. In another school of thought, the asteroid belt was born with very little mass in planetesimals, which were dynamically excited by the chaotic evolution of Jupiter and Saturn during the giant planet stability phase. This talk will focus on how the asteroid belt's mass and orbital structure constrains models of Solar System formation.
Reference:
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Pieces of Planets in the Asteroid Belt

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Abstract

Collisions between large planetary embryos are common during the era of terrestrial planet formation. While these collisions are responsible for planetary growth and the formation of Earth’s Moon, they also may eject impact debris into heliocentric orbit. In the past, planet formation has historically been studied assuming perfect accretion—the total of the target’s and projectile’s mass ends up in the resulting body. Here, we break this assumption to understand the role of impact debris created during giant impacts. We implemented a full collision model developed from hydrodynamical and particle simulations (Leinhardt & Stewart 2011) inside an N-body planet formation algorithm (Symba; Levison & Levison 2000), which we used to simulate the formation of the terrestrial planets. Using this model, we show that the debris is quickly scattered from the planet forming region with approximately 1/3 ending up in the Sun, 1/3 on the target embryo of the collision which ejected the Mass,
1/3 on other embryos in the simulation. However, approximately a percent of the debris ends up on stable orbits scattered throughout the Main Belt. Prior to considering the ejected debris from giant impacts, the asteroid belt was presumed to consist of leftover planetesimals and their fragments, but now we conclude that amongst differentiated asteroids and achondritic meteorites that the forming planets could be a significant source.

Reference:

Physics of asteroid collisions

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Abstract

The objects of the Asteroid Main Belt are a result of a billion-year-long collisional evolution of varying intensity. Their current shape, structure and composition provide important clues to their origin and history, and therefore represent a window to the early stages of the formation of the Solar System. Asteroids smaller than about 50 km in diameter are the result of a break-up of a larger parent body. Their properties such as their shapes, interior structure and spin state are determined to a large degree by the last major (global scale) impact event. Important questions are how much asteroids were processed by past collisions and to what extend they retained a record of processes that took place during the formation and early evolution of the Solar System. The degree of impact processing depends not only on the intensity of the bombardment, but also on the properties (density, porosity, strength, etc.) of the bodies involved.

As a complement to experimental and theoretical approaches, numerical modeling, using so-called “hydrocodes” or “shock-
physics codes”, has become an important component to study asteroid collisions. Recent progress has allowed for the simulation of the entire process, the collisional disruption followed by the gravitational re-accumulation, and to compute the final shapes and structures of the objects resulting from such events. However, the realistic modeling of small body collisions is highly complex and the current models are still limited by a number of simplifications.

In this talk I will discuss the state-of-the-art models and the relevant physical processes that determine the fate of asteroids in energetic collisions. The objects resulting from such asteroid disruptions will be analysed in terms of their overall properties (e.g. shape and interior structure) and the degree of material processing (e.g. heating and compaction). Some results of recent studies performed in this context will be presented.

**Reference:**
Turbulent Diffusion regulated Asteroid Formation in Trapping Mode

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Abstract

Self Gravity is the dominant effect to form planetesimals. Formation in trapping modes claims that first the radial pebble flux is trapped in zonal flows and vortices. Once the local pebble concentration is sufficiently high to allow self-gravity to overcome turbulent diffusion, collapse on a characteristic length-scale will occur. This length-scale in combination with the critical density for collapse, i.e. Hill-density leads to a mass prediction for first generation planetesimals in the solar nebula on the order of about 50km in radius. We show numerical simulations of the onset of pebble cloud collapse in a turbulent gas simulation of the streaming instability. We also show results of N-body simulations on the further fate of the collapsing rotating pebble cloud, forming solid objects and discuss their initial shape, binarity and spin. We also present semi-analytic models of planetesimal formation in the Solar Nebula, indicating the time sequence of asteroid formation. As an interesting result we find the local asteroid to gas ratio to be larger than the original dust to gas ratio, which is a
consequence of planetesimal formation from pebbles in trapping mode.

Reference:


Volatile loss from differentiated protoplanets during catastrophic disruptions

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Abstract

The terrestrial planets and some differentiated asteroids are strongly depleted in moderately volatile elements (i.e., elements having condensation temperatures between ~1250 and ~650 K) relative to the composition of CI chondrites and the Sun. However, the origin of these volatile element depletions and whether they result from processes associated with planetary accretion and differentiation or from prior fractionations in the solar nebula are unclear. Group IVB irons are among the most strongly volatile-depleted meteorites [1], yet their parent body presumably formed beyond the ice line [2], implying that its precursor material was volatile-rich initially. This raises the question of when and how the IVB parent body or its precursors lost their volatiles. Here we address this issue using the short-lived 107Pd-107Ag system (half-life ~6.5 Ma), which is ideally suited to date iron meteorites and, because Ag is volatile, also to determine the
timescale of volatile fractionation [3,4]. Our results show that the IVB irons are characterized by exceedingly high Pd/Ag ratios combined with a 'young' Pd-Ag age of 8–14 Ma after CAI formation. Yet, their initial Ag isotopic is unradiogenic, indicating that the high Pd/Ag of the IVB core was established just prior to core crystallization and cooling. These observations are best accounted for by collision between two differentiated bodies, resulting in mantle stripping and exposure of the still molten IVB core . This process likely facilitated volatile loss by degassing, because the removal of the mantle resulted in pressure release, which in turn reduces the solubilities of volatile species in the metallic magma and promotes degassing of Ag and other volatile elements.

Reference:
A Synthetic Method to Determine Positions of Secular Resonances

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Abstract

Strong secular resonances are among the main drivers of the depletion of asteroids from the corresponding regions in the Main Belt. It is, therefore, important to know their positions with best possible accuracy. Following the method used to assess the structure of secular resonances in the Trojan region (Milani, 1994), we developed a new synthetic method to determine the positions of secular resonances in the asteroid Main Belt. The method consist of a polynomial fit to the secular rates of the asteroid perihelia and nodes derived by means of the synthetic theory (Knežević and Milani, 2000), computation of the corresponding values for regular grid of points in the space of proper elements, and defining the contour lines corresponding to a given small value of the resonant frequency. Degree of the polynomial used for the fit and other relevant parameters are adjusted to the specific
dynamics in different parts of the Belt. We present the method and some representative results, discussing their accuracy in comparison with the previously available ones, obtained from the analytical theory. We also show resonance maps in the frequency space, including positions of linear and nonlinear resonances corresponding to perturbing terms of up to degree 6 in eccentricity and inclination.

Reference:

Dimensionality of asteroid spin phase space

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Abstract

In Medeiros et al. (2018) we presented a systematic study of the spin distribution of asteroids. It was clearly shown that these distributions behave as if the rotational phase-space of the heavier main belt asteroids is two dimensional rather than three dimensional as usually assumed, particularly for those objects with diameter larger than 50 km. For lower mass objects, the dimensionality deduced from the data is even less, reaching to 1(one), which is consistent to the known mechanism such as YORP. In this study, we investigate some physical possibilities from where this somewhat “strange” dimensionality 2 (neither 1 nor 3) comes from. This may cast interesting open questions on the origin of asteroid rotation.

Reference:
The NC-CC meteorite dichotomy and its implications for early Solar System evolution

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Abstract

Isotopic studies of meteorites can help to reconstruct the earliest evolution of the Solar System and provide crucial insights into the processes of planetary growth. Though until recently meteorites were merely viewed as samples of small bodies that presumably formed in the asteroid belt, this perspective has changed dramatically with the discovery of a fundamental genetic dichotomy in the meteorite population, distinguishing between separate carbonaceous (NC) and non-carbonaceous (NC) solar disk reservoirs [1]. Here we review the isotopic evidence for this NC-CC dichotomy and highlight its implications for the large-scale dynamics and structure of the solar protoplanetary disk. The NC-CC dichotomy was first discovered based on Cr, Ti and O isotope anomalies in
meteorites which define two separate clusters, implying a lack of mixing between two solar disk reservoirs [1]. Subsequent work revealed that this NC-CC dichotomy also exists for other elements (e.g. Mo, Ni, Ru) and extends to iron meteorites [2-4], demonstrating that both the NC and CC reservoirs contained differentiated and undifferentiated planetesimals.

The NC-CC dichotomy fundamentally changes our understanding of the early Solar System, and when integrated with astrophysical models, provides crucial insights into the dynamics and large-scale structure of the solar accretion disk. In particular, the ages and genetics of iron meteorite and chondrites imply an early and protracted spatial separation of inner (NC) and outer (CC) disk reservoirs, lasting between ~1 and ~4 Ma after the first solids [3]. This effective spatial separation is most easily reconciled with the early growth of Jupiter’s core [2,3], acting as a barrier and inhibiting significant exchange of material within the disk [e.g. 5]. This finding is in excellent agreement with pebble accretion scenarios promoting rapid growth of protoplanetary cores including those of gas giants [6]. Following Jupiter’s early growth, CC bodies must have scattered from the outer Solar System into the asteroid belt, which requires that Jupiter opened a gap within a disk and/or migrated inward [e.g. 5]. Thus, the NC-CC dichotomy and the early growth of Jupiter are remarkably consistent with current giant planet migration models including the Grand Tack [7].
Although its exact origin is still being investigated, the NC-CC dichotomy is consistent with a higher fraction of presolar carrier phases containing nuclides produced in neutron-rich stellar environments in the CC over the NC reservoir [1,2,4]. This characteristic is most readily accounted for by an isotopic change in the composition of the infalling material from the Solar System’s protostellar envelope [4], resulting in the formation of distinct inner (NC) and outer disk (CC) reservoirs which were then preserved for several Ma by the Jupiter barrier [3].

Reference:
Chemical characterization of comets of various dynamical classes: is the observed heterogeneity primordial or evolutionary?

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Abstract

Taxonomic classification of comets based on their volatile chemical composition suggests that comets are different depending on their formation zone (A'Hearn et al., 1995; Fink, 2009). However recent Solar System formation models (Brasser and Morbidelli, 2013) suggest that comets formed all in the same region before being scattered to the various reservoirs. If this scenario is confirmed, the observed chemical diversity should be interpreted as evolutionary, rather than primordial, thus opening new perspectives on the early evolution of comets. We will present spectroscopic data of 12 comets of various dynamical classes (Jupiter family comets...
(JFC), Encke type, Halley type, hyperbolic etc.) in the full UVB+VIS+NIR spectral range observed through TNG telescope at La Palma, and possibly part of the 21 comets that will be observed in the next semester at ESO-VLT telescope. We will present cometary volatile composition studied through UV and visible bands (OH, CN, C2, C3, NH2, O(1D)) and NIR emission features (CN, C2 and H2O). Such extensive characterization of comets of various dynamical classes will allow to test the recent dynamical models and help in understanding if the observed heterogeneity is primordial or evolutionary.

Reference:

Fink et al., 2009, Icarus, 201, 1.

Estimations of Masses of Non-Observed ‘Tails’ of the Asteroids Families

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Abstract

Selection of some Asteroid Families (AF) from the data set containing more than 400000 numbered asteroids was the first step of this work. Hierarchical Clustering Method (HCM) of selection was applied. A full set of the N Asteroid Family Members (AFMs) of the considered family was ranged according to their masse (the density is assumed to be known). Next, the assumed formula for asteroid mass distribution \( dn = B m^{-\gamma} dm \) was fitted in several intervals \((n_1, n_2)\) where \(1 < n_1 < n_2 < N\). It was found, that the both parameters \((B, \gamma)\) decreases when the interval \((n_1, n_2)\) shifts to the larger numbers. This trend holds for all AFs considered. Basing of this we extrapolated mass distribution of each AF up to indefinitely small masses. This extrapolation allowed us to calculate the masses of the ‘tails’ composed of
small asteroids. Of them most are non-observable. In consequence the masses of the AFs are calculated. The latter are the lower limits of mass of the Parent Bodies (PBs) from which the families has been formed following an impact.

Families considered in this work are 4 Vesta (0.0008), 221 Eos (0.7), 15 Eunomia (0.08), 20 Massalia (0.1), 24 Themis (0.6), 158 Koronis (0.95), and 3815 Koenig (0.89). The figures in brackets denotes approximate values of the fraction $f$ of primary mass $MPB$ lost from the PB after an impact. Of these values considerable parts are the masses of the non-observed tails.

Reference:

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Embedding Planetsimals in the Asteroid Belt During Giant Planet Formation

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Abstract

The asteroid belt is observed to be a mixture of objects with different compositions, with volatile-poor asteroids (mostly S-complex) dominant in the inner asteroid belt while volatile-rich (mostly C-complex) asteroids dominate the outer asteroid belt. While this general compositional stratification was originally thought to be an indicator of the primordial temperature gradient in the protoplanetary disk, the very distinct properties of these populations suggest that they must represent two completely decoupled reservoirs, not a simple gradient (e.g., Warren 2011). It is possible to create this general stratification (as well as the observed mixing) as the implantation of outer Solar System material into the asteroid belt by the early migration of the giant planets (e.g. the Grand Tack, Walsh et al. 2011). However, this presupposes that the inner and outer Solar System materials were still sorted in their primordial locations prior to any migration of the
planets. The lack of a fully dynamically self-consistent model of giant planet core formation has prevented the study of how the core formation process itself may result in dynamical mixing in the early Solar System's history. Recently, pebble accretion, the process by which planetesimals can grow to giant planet cores via the accretion of small, rapidly drifting sub-meter-sized bodies known as "pebbles," (Lambrechts & Johansen 2012, Levison, Kretke & Duncan 2015) finally offers such a model. Here we show how the process of giant planet formation will impact the surrounding planetesimal population, possibly resulting in the observed compositional mixture of the asteroid belt, without requiring a dramatic migration of the giant planets. For example, preliminary runs suggest planetesimals from the Jupiter-formation zone can be implanted in the outer main belt via interactions with scattered Jupiter-zone protoplanets. This could potentially provide a solution to the origin of many C-complex bodies, including Ceres.

Reference:
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The spectral properties of the Lixiaohua family, cradel of Main Belt Comets

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Abstract

The Lixiaohua collisional family lies in the Outer Main Belt, close to the well characterized Themis (and its Beagle sub-family) and Veritas family of primitive class asteroids. It is one of the only three families that hosts two active asteroids that present cometary-like activity (P/2012 T1 and 313P, Hsieh et al., 2013, 2015b).

We present results of a visible and infrared spectroscopic program using the 10.4m Gran Telescopio Canarias, the 4.1m SOAR and the 3.56m Telescopio Nazionale Galileo. We
observed a significant number of Lixiaohua asteroids with the aim of studying the family in order to: (1) accurately determine the spectral class and spectroscopic properties of the family; (2) measure the water content by studying the 700nm absorption band and the UV drop below 500nm due to hydrated minerals on their surfaces and derive information about the mineralogical composition and degree of differentiation of the family parent body, (3) allow to have a future spectral confirmation that active asteroids P/2012 T1 and 313P are real family members as we did in Licandro et al. (2011, 2013).

The study of the collisional families that host the Main Belt Comets is of fundamental importance to understand their activation mechanisms and the abundance of water in the main belt.

**Reference:**


Ceres and Vesta: Understanding the Protoplanets of the Asteroid Belt

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Abstract

The largest asteroids Vesta and Ceres are likely relics from planetesimal formation processes in the primordial Solar System.

In the case of the 500-km rocky Vesta, the study of howardite, eucrite and diogenite meteorites—supposedly fragments of Vesta's crust—have shown that it formed within the first 2-4 Myr after the condensation of the first solids in the protoplanetary nebula [1]. Furthermore, gravity data gathered by the Dawn spacecraft have shown that Vesta is an intact, fully differentiated body with a ~110 km diameter metallic core [2].

The origin of the 950-km Ceres remains more elusive, partly because we have yet to find meteorites consistent with Ceres's surface, but also because of its peculiar surface composition. The detection of ammoniated phyllosilicates and carbonates [3], along with a moderate central mass
concentration [4], indicates Ceres underwent a radically different internal evolution compared to its sibling Vesta.

Dawn has shown that the two most massive bodies in the main belt (comprising about 40% of the total mass), appear to have a very distinct nature, raising the question of whether they formed in situ or were transported on their current orbits at a later epoch [3, 5]. Transport and implantation of objects into the main belt is permitted by some Solar System formation and evolution models [e.g., 6]. These models envision dynamically-driven displacement of planetesimals over a wide range of heliocentric distances, and a fraction of the mobilized objects is captured within the current boundaries of the main belt.

In this talk I will discuss Dawn data at Vesta and Ceres and will place constraints on our ever-changing views of main belt formation.

**Reference:**


Spectroscopic properties of basaltic asteroids: hints on the origin of V-types outside the Vesta family region

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Abstract

Basaltic asteroids are distributed throughout the Main Belt, from the NEA region to the outer belt. Although only asteroid 4 Vesta is recognized to date as the parent body of these asteroids, spectral properties for most of the observed V-types, especially located in the mid-outer regions, possibly indicate a different origin.

In the last decade, we performed vis-nir spectroscopy for more than 70 asteroids, classified as possible V-types on the basis of their photometric colors in the visible [Roig and Gil-

We obtained mineralogical information for these asteroids in the wavelength range 0.3-2.5 μm, observed during several runs at Telescopio Nazionale Galileo (La Palma) and Very Large Telescope (ESO, Paranal).

Comparisons of the observed asteroids with Howardite-Eucrite-Diogenite meteorites and the Vesta’s surface, as it resulted from the VIR/Dawn spectrometer, allowed identifying possible links with regions on the Vesta surface.

A better knowledge of the differences and similarities between V-type asteroids all around the Main Belt has, thus, been attained improving our understanding of the origin of basaltic material in the Solar System [De Sanctis et al., 2012a, MNRAS; De Sanctis et al., 2012b, A&A; Migliorini et al., 2017, MNRAS; Migliorini et al., 2018, MNRAS].

In the present work, we summarize the results obtained in 13 years of observations of V-type asteroids, performed at Telescopio Nazionale Galileo and Very Large Telescope.

Hints on the origin of confirmed basaltic asteroids in the middle and outer belt are also presented.

Reference:
Carvano et al., 2010, A&A;
De Sanctis et al., 2012a, MNRAS;
De Sanctis et al., 2012b, A&A;
Licandro et al., 2017, A&A;
Migliorini et al., 2017, MNRAS;
Migliorini et al., 2018, MNRAS;
Roig and Gil-Hutton et al., 2006, Icarus.
Non-solar Al/Si and Mg/Si ratios of the Earth and enstatite chondrites reveal planetesimal formation during early condensation in the protoplanetary disk

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Abstract

The Al/Si and Mg/Si ratios in the Earth and in enstatite/ordinary chondrites are respectively larger and smaller than the solar (i.e. CI-chondritic) values. This excludes the possibility that the Earth is predominantly made of enstatite chondrites, despite the close similarities in isotope compositions. We show that the accretion of a first generation of planetesimals during the condensation sequence of refractory elements implies the subsequent formation of residual condensates with strongly sub-CI Al/Si and Mg/Si ratios. The mixing of residual condensates with different amounts of material with CI-like refractory element ratios explains the Al/Si and Mg/Si values of enstatite and ordinary chondrites. The combination of first-formed planetesimals from incompletely condensed material, possessing strongly fractionated Al/Si and Mg/Si ratios, with enstatite chondrites
or CI-like material can then explain the values of these ratios in the Earth. To match quantitatively the observed ratios, we find that the first-planetesimals should have accreted when the disk temperature was 1,400K-1,425K at an assumed disk's pressure of 1.e-3 bar. We discuss how this model relates to our current understanding of disk evolution, grain dynamics, and planetesimal formation. We also show that this new view of the genetic relationship between the Earth and enstatite chondrites resolves the conundrum of their differences in element composition yet their similarities in isotope compositions. The slight differences in some isotope ratios between Earth and enstatite chondrites can also be understood in the framework of this model. We also extend the discussion to the enrichment of enstatite and ordinary chondrites in moderate volatile elements (e.g. Na) compared to non-CI carbonaceous chondrites.

Reference:
submitted to EPSL
Implantation of Bodies into the Asteroid Belt

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Abstract

Models of the formation and early evolution of the solar system suggest that small bodies were radially redistributed by growing and migrating planets. A fraction of the original population of small bodies eventually ended on stable orbits in the asteroid belt (2-4 au). First, during an early episode of gas-driven migration of Jupiter, C-type asteroids have been presumably implanted into the asteroid belt from ~5-15 au. Their implantation was helped by aerodynamic gas drag and could have happened even if Jupiter has not migrated. Second, D-type asteroids that presumably formed beyond ~15 au, could have been implanted into the asteroid belt during planetesimal-driven migration of the outer planets. If this is correct, the asteroid taxonomy provides clues about the gradient in physical properties of planetesimals well beyond the radial extension of the current asteroid belt.

Reference:
Synthetic model of a "random" asteroid belt population in the proper elements space

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Abstract

It is well known that for any study of long-term dynamical evolution of asteroids, proper orbital elements are more suitable than the instantaneous osculating ones. However, proper elements based studies should take into account that orbital distribution in proper element space has its own peculiarities. Concerning numerically obtained, the so-called synthetic proper elements, there are two main sources of these undesirable effects. First, in order to obtain the synthetic proper elements, orbits of asteroids are propagated over an adequate timespan. During these integrations however, trajectories of non-stable objects evolve, and in some cases the level of change is large enough to even prevent computation of the proper elements. Second, averaging procedures incorporated in process of computation of this type of orbital elements are not fully appropriate for resonant objects. The first problem is usually producing almost
empty regions in orbital distribution of asteroids, while the second one is causing artificial concentration of objects around centers of the resonances. As a result, starting from a fully uniform distribution of asteroids in the osculating elements space, the obtained distribution in the proper elements is notably non-uniform.

Here we investigate in details structures in the orbital distribution of main belt asteroids, produced during the process of computation of the proper elements. To achieve this aim we create an artificial population of $10^6$ objects uniformly covering the region of asteroid belt in osculating elements, and compute the synthetic proper elements for all of them, following exactly the same methodology usually employed to compute these elements for real objects.

The results may be considered as a synthetic "random" model of asteroid belt in the proper elements space.

The main purpose of this is to discriminate the orbital structures produced by procedures used to compute proper elements themselves, from the real structures in orbital distribution. We have also demonstrated how the result may be used to increase statistical significance of identified asteroid families and possibly to identified new families.
Reference:

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Asteroid Families Portal

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Abstract

A possible way to cope with the large size and complexity of data accumulated in the recent years is development of web-portals. Such portals are often devoted to specific purposes, and allow scientists to easily review and analyze different data. Here we present an open access web portal devoted to asteroid families, namely the Asteroid Families Portal (AFP).

The aim of the AFP is to collect different data about asteroid families and closely related subjects. The portal can be used to quickly assess and visualized data, but this should not be its only purpose. Our aim is to provide different tools and methods to analyze collected data and to study families in general. For instance, the well-known Hierarchical Clustering Method (HCM) could be employed on-line to obtained the most recent list of a family members, while the Backward Integration Method (BIM) could be used to estimate ages of asteroid families younger than 10 Myrs. Other services currently implemented at the AFP include an automatic procedure to obtain a list of family interlopers, and a list of the
most recent journal papers on asteroid families. Last but not least, the AFP is providing the proper orbital elements of numbered as well as of active asteroids.

The AFP is foreseen to be continuously updated and upgraded. For instance, we foresee to offer a fully automatic estimation of family age, based on the so-called V-shape method. We also aim to develop an algorithm that will provide different basic information about an asteroid family, such is the size of the parent body and its corresponding escape velocity, the slope of the magnitude-frequency distribution, etc.

Reference:

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A contribution to the understanding of the evolution of the Belt: estimating the ages of asteroid families

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Abstract

Improved computation of asteroid proper elements and classification of dynamical families have allowed a more thorough and detailed analysis of their structure. In turn, more robust and significant inferences on their original properties and evolution have been obtained. Among them, estimates of the age, based on the slope of the so-called V-plot, on the location of the so-called YORP-eye, and also on other criteria. A more detailed analysis of the V-plot, and improved age estimates are presented.

Reference:
Milani et al, 2014 Icarus 239, 46
Spoto et al. 2015 Icarus 257, 275
Paolicchi & Knezevic 2016 Icarus 274, 314
Milani et al. 2017 Icarus 288, 240
Paolicchi et al. 2019 MNRAS in press
Detection of aliphatic organics on comet 67P
reinforces the “comet-asteroid continuum”

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Abstract

The VIRTIS infrared spectra of the surface of comet 67P/Churyumov-Gerasimenko (67P/CG) display a wide absorption band in the range 2.8-3.6 μm, which has been associated to the presence of organic compounds [1, 2]. However, several instrumental effects have hindered, so far, the detailed interpretation of the molecules and compounds contributing to this band. In this work we first revise the calibration of the VIRTIS-M-IR instrument [3, 4] onboard the Rosetta spacecraft with the aim to improve the detection of low-contrast spectral features and the radiometric accuracy.

Multiple observations of the nucleus during the inbound part of 67P/CG’s orbit (August-September 2014) are processed to derive an average reflectance spectrum to minimize the Poissonian noise. The refined calibration applied to it includes: i) the removal of artifacts associated to calibration residuals and/or incomplete flat field correction; ii) the reduction of non-Poissonian noise introduced by the readout electronics of the instrument; iii) a newer version of the radiometric calibration using stellar sources. Furthermore, we have modeled the thermal emission from the nucleus to remove its contribution longward of 3.0 μm. This refined analysis reveals a complex internal structure within the wide 2.8-3.6 μm absorption feature. Individual sub-features can be
unambiguously identified after correction. The strongest ones are centered at 3.1, 3.3, 3.38, 3.42, 3.47 μm.

Two main aspects of the refined average spectrum corroborate the so called “comet-asteroid continuum” hypothesis, blurring the distinction between different classes of objects:

1) clear evidence of aliphatic compounds (CH2 and CH3) is given by the presence of the 3.38, 3.42 and 3.47 μm absorption bands. These features have never been observed on a cometary nucleus before. The spectral properties of the aliphatic signatures have striking similarities to that of the Insoluble Organic Matter extracted from primitive Carbonaceous Chondrites;

2) the overall shape of the spectrum presents similarities with some main belt and outer solar system objects, in particular, the presence of absorptions at 3.1 μm and in the spectral range 3.3-3.4 μm.

These findings allow a better understanding of the formation and evolutionary processes by suggesting a genetic link between comets and other pristine solar system materials (Raponi et al., Science, submitted).

Acknowledgements: We thank the following institutions and agencies for support of this work: Italian Space Agency (ASI,
Italy) Centre National d'Etudes Spatiales (CNES, France), DLR (Germany). This work takes advantage of the collaboration of the ISSI international team “Comet 67P/Churyumov-Gerasimenko Surface Composition as a Playground for Radiative Transfer Modeling and Laboratory Measurements”, number 397.

Reference:
Abstract

Prior to the Dawn mission, it was already known that Vesta and Ceres, the most massive bodies in the main belt, had divergent histories. Vesta’s surface was very similar to basaltic achondrite meteorites [1], and Ceres had affinity to primitive carbonaceous chondrites [2, 3]. Ceres’ mass and size provided a density of ~2.1 g/cm³, indicating significant water content (~25% by mass), and thermodynamic modeling [4, 5] yielded heating, ice melting and silicate hydrothermal alteration with mass differentiation. Vesta was known to be dense (~3.46
$g/cm^3$), suggesting a dry, hot history [6]. Prior to the Nice [7] and Grand Tack [8] models, it was thought that Ceres and Vesta formed in the same part of the disk near their current location [9], and their differences were ascribed to a later formation of Ceres with respect to Vesta. The Dawn mission’s exploration of Vesta and Ceres [10] has advanced our knowledge of their internal evolution, surface geology and composition, elucidating their early histories and adding constraints on early solar system processes. Dawn confirmed that Vesta experienced extensive silicate melting and differentiation, resulting from a hot, dry evolution [11] and that Ceres had a much milder thermal history, resulting in only partial differentiation and retention of volatiles [12-15]. This contrast can be primarily attributed to the abundance of water in Ceres that moderated internal temperature via latent heat and hydrothermal circulation [5, 16]. It has been suggested that Vesta and Ceres accreted from similar chondritic feedstocks but at different times, i.e., with different short-lived radioisotope budgets [4, 9]. However, it also seems likely that the starting composition of Vesta and Ceres was very different, especially in terms of ice abundance. Discovery of ammoniated clays on Ceres [17] indicate Ceres itself or its accreted constituents formed in the outer solar system. Multiple models have attempted to explain the origin of volatiles in the asteroid belt, and several distinct episodes of volatile migration have been suggested. While planetesimal
migration across the gap in the disk opened by Jupiter likely lead to de-volatilization of small planetesimals [18], larger planetesimals (1-10s km) may have migrated following destabilization by the growing giant planets [19]. Post-Dawn, the consensus view is that Ceres formed in the region between the giant planets, as one of a class of large planetesimals predicted by recent accretion models [20], and was implanted into the main belt during early giant planet migration [21].

Reference:


Part of this work is being carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract to NASA.
Cosmolocation using nucleosynthetic isotope anomalies in meteorites

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Abstract

Reconstructing the primordial architecture of the protoplanetary disk is of paramount importance if we are to understand how the Solar System evolved structurally and arrived at its current configuration. Mass-independent isotope anomalies of nucleosynthetic origin are a promising tool to shed light on this issue, as they provide a direct record of the planet building material, and are not easily overprinted. Previous studies have shown that certain types of meteorites are isotopically different from the bulk silicate Earth (BSE) in many elements, which has been attributed to the heterogeneous distribution of isotopically anomalous presolar matter throughout the protoplanetary disk [e.g., 1].

As a lithophile element with seven stable isotopes produced by varying proportions of the p-, s-, and r-process of nucleosynthesis, neodymium (Nd) is a particularly interesting element for nucleosynthetic studies. In addition, two Nd nuclides (142,143Nd) are of partial radiogenic origin, providing
insights into the early evolution and the heat budget of planetesimals and the terrestrial planets. Here we investigate a set of five angrites and six eucrites for their Nd isotopic compositions in order to locate their original accretion region and, possibly, to assess their role in the accretion history of Earth.

Relative to the BSE, the investigated achondrites all exhibit deficits in Nd nuclides produced by the s-process and are slightly more s-depleted than enstatite and ordinary chondrites reported in [2]. When these Nd isotope data are layered with other elements—such as Mo and Ru, which similarly show s-process deficits relative to the BSE in these meteorites [3-6]—fine-scale reconstruction of the original formation location of these parent bodies becomes conceivable. As meteorite parent bodies are built from the material present in their feeding zones, the differences in the amount of s-process isotopes may be seen as a captured signature of original heliocentric distance of formation. Due to the fact that these nucleosynthetic anomalies trace the primary building material—prior to disturbances from the subsequent migrations of the gas giants—this technique could render the amount of s-process matter in Nd, Ru, and Mo useful tools for ‘cosmolocating’ the accretion orbits of meteorite parent bodies.
Reference:


A New Asteroid Taxonomy based on Photometric Colors: Application to Dynamical Structure of the Main Belt

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Abstract

Dynamical structure of the Main Belt has been explored for decades using proper orbital elements, quasi integrals of motions, to reconstruct its past history. Recently, large-scale sky surveys such as Sloan Digital Sky Survey (SDSS) shed new lights on dynamical studies of the Main Belt with characteristic proper elements and visible colors of different dynamical groups called asteroid families. The “color-coded” data points (individual asteroids) in the orbital phase space form ~100 distinct groups which are easily distinguishable. Thus, a proper taxonomic classification is considered to be an aid to unambiguously discriminate different asteroid families, and finally provides a high resolution picture of the Main Belt. However, the currently used taxonomic classifications of asteroids have some shortcomings; the boundaries of each class are rather ambiguous. We present a new concept of
asteroid taxonomy. Our approach is simply represented by three indices of SDSS colors. The centers of each taxonomic class are determined mathematically and the class boundaries are statistically established. We apply our scheme to MOC 4 calibrated with VIS-NIR reflectance spectra of DeMeo and Carry, and improve the ambiguity of their taxonomic classification results with the 2-dimensional parameter space (e.g., spectral slope vs. i-z reflectance). We separate seven different taxonomic classifications: C, D, K, L, S, V, and X, with which we have a relatively sufficient number of spectroscopic datasets. We then apply the newly defined taxonomic classes to a number of interesting asteroid families defined by Nesvorny et al. (2015). In this paper, we will present highlights of our preliminary results. We have the careful optimism that the taxonomic distributions of asteroid families in the proper orbital element space may reveal the possibility of a more detailed interpretation for the origin and evolution across the Main Belt.

**Reference:**


Nesvorny, D (2015) PDSS, 234

Constraints from isotopic compositions of meteorites: II. Implications for less common asteroid types (A, M, V, E and L)

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Abstract

Introduction: In a companion abstract [1] we discuss the formation of the asteroid belt knowing that meteorites fall into two distinct isotopic classes, carbonaceous (CC) and non-carbonaceous (NC). We discuss how the two classes probably originated, respectively, outside and inside Jupiter’s orbit, and how the predominant meteorites of each class, carbonaceous and ordinary chondrites, come from C–type and S–type asteroids. Here we extend the discussion to other asteroid types.

A, M and V–types: These three types probably supply olivine-rich, iron, and basaltic meteorites, respectively, which, unlike chondrites, are differentiated (made by melting). Differentiated meteorites occur in both the NC and CC classes.
Hence some A, M and V–types presumably migrated sunwards from beyond Jupiter, consistent with their broad distribution across the belt [2]. They are much rarer than C and S–types, just as differentiated meteorites are rarer than chondrites, but, intriguingly, differentiated meteorites sample about four times as many individual parent bodies as chondrites [3]. A plausible reason for this puzzling disparity is that asteroids are not original parent bodies, but are derived from the latter by extensive reprocessing (Ceres and Vesta are exceptions). Differentiated bodies accreted early, melted quickly (by 26Al heating), and were generally lost in hit-and-run impacts, in mergers with protoplanets, and conceivably through conversion to chondrules [4]. A small fraction of each ‘lost’ body was, perhaps, ejected as collision fragments, ending up preserved sparsely in rubble-pile asteroids, to be released sporadically as rare, multi-sourced, differentiated meteorites. Chondritic meteorites (and asteroids), in contrast, are abundant perhaps because they are the final accumulation of multiply recycled debris [4], accreted >2.5 Myr after CAIs (so didn’t melt), and, being porous, are resilient under bombardment [5].

E–type asteroids: These are concentrated in the inner belt, but were probably scattered there after accreting close to Earth’s orbit because their related meteorites, E-achondrites (aubrites), are isotopically very like the Earth [6]. S–type asteroids, in contrast, probably accreted beyond Mars’ orbit,
in the main belt, because ordinary chondrites (samples of S–types) plot isotopically (e.g. $^{54}\text{Cr}$ vs $^{50}\text{Ti}$) on the far side of Mars relative to Earth [7].

L–type asteroids: Modeling and laboratory studies [8] suggest that L–types (spinel-bearing) may contain 30 vol.% CAIs. Since CAIs formed at $t_0$, probably close to the protosun [9], L-types are commonly thought to have accreted soon after CAIs in the inner solar system. However, CAIs are rare except in carbonaceous chondrites, so were presumably delivered directly to the CC reservoir (outer disk) then drifted inwards and accumulated (along with ice particles [10]) at the ‘Jupiter gap’ pressure barrier [7,11]. This would explain the abundant CAIs (and water) in carbonaceous chondrites, and suggests that CAI–rich L-type asteroids accreted outside Jupiter.

Reference:


Atmospheric noble gas isotope and bulk K/U ratios as a constraint on the origin and early evolution of Venus and Earth

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Abstract

While Venus and Earth were accumulating mass within the solar nebular these protoplanets also captured significant hydrogen dominated atmospheres by picking up gas from the
circumstellar disk during the formation of the Solar System (e.g. Stökl et al. 2016). These primordial atmospheres were then quickly lost by hydrodynamic escape after the disk dissipated. After a short but efficient boil-off phase the EUV-driven hydrodynamic flow of H atoms dragged heavier elements with it at different rates, leading to changes in their isotopic and elemental ratios (Zahnle and Kasting 1986, Hunten et al. 1987, Odert et al. 2018), which is reflected in the present-day atmospheric noble gas isotope and elemental ratios of Venus and Earth. Depending on the disk lifetime and the initial composition of the protoplanets, we find that the atmospheric 36Ar/38Ar, 20Ne/22Ne, and bulk K/U ratios observed for both planets can be best explained if the Sun was born between a weakly and moderately active star and if Venus and Earth had grown to ~85-100% and ~53-58% respectively of their current masses by the time the nebula gas dissipated approximately 3.5 Myr after formation of the Sun. If proto-Earth accreted its mass from ~60% volatile poor ureilite-like and 40% carbonatious chondritic-like material (Schiller et al. 2018) then the planet must have been grown to about 80% of its final mass as long as it was surrounded by the escaping primordial atmosphere (~7 Myr). Our results are therefore in agreement with a fast accretion of thermally-processed disk material into asteroidal bodies and/or planetary embryos, as well as Hafnium-Tungsten chronometric fast accretion scenarios of the proto-Earth (e.g. Yu & Jacobsen
2011), as well as a noble gas origin based on a mixture of primitive meteoroids and a small remnant of the proto-solar nebula (Marty 2012). This also indicates that a significant amount of the terrestrial building blocks were delivered from behind the so-called snow line early-on.

Reference:


Ryugu as seen up close by the MASCOT camera

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Abstract

The MASCOT lander was dropped by the JAXA Hayabusa2 spacecraft towards the surface of C-type asteroid Ryugu on October 3, 2018. It successfully settled on the surface and, after activating an internal mobility unit, achieved the desired orientation for an in-situ observational campaign. The on-board camera (MasCam) imaged the surface during the descent and over the course of two asteroid nights and days according to a robust observational plan. During the night, illumination was provided by an on-board array of LEDs in four colors. MasCam showed the Ryugu surface to be extremely rough, with rocks and boulders, but without fine regolith. Images acquired during the descent reveal two dominant rock types: (1) rocks with smooth, angular features and linear fractures, and (2) rocks with a very rough, crumbly surface. After landing, MASCOT successfully re-oriented itself to achieve the optimum observation geometry for MasCam. A
wealth of data was acquired, with the asteroid surface clearly visible at close range. Dominating MasCam's field-of-view is a small rock, whose surface is resolved at a spatial resolution of 0.25 mm per pixel. The day images reveal the rock to have a high surface roughness, and we recognize it as a type 2. Night images were acquired in four colors using the on-board LEDs to assess color variability. Thanks to the small phase angle of the LED observations, the presence of many small, bright inclusions set in a dark matrix was revealed. The inclusions exhibit a surprisingly large range of spectral variation in the visible wavelength range, with apparent colors ranging from blue, via yellow, to red. The presence of abundant multi-colored, chondrule-sized inclusions in this Ryugu rock provides a link between C-type asteroids and carbonaceous chondrites. To further explore this link, we study the inclusion abundance and size distribution, and compare with published meteorite statistics.

Reference:

-
Surface Dating of Asteroids by Luminescence Measurements from Orbit

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Abstract

Determining the geological age of the objects in the main asteroid belt provides one key to understanding its formation and overall evolution. Currently, the age of an asteroid can be determined reliably only by laboratory measurements of returned samples, or by in-situ surface measurements. Either is very expensive. Hence, to determined the age of many asteroids, a relatively inexpensive technique is needed that can determine from an orbiting spacecraft the relative age, level of "gardening" and rough composition of the surface, and their relation to surface morphological features. Optically stimulated luminescence (OSL) dosimetry could allow the determination of the age, and to a certain extend, composition of an airless body, such as an asteroid, by remote-sensing from orbit. The technique is well known from archaeology and may be adapted to geological timescales. It is based on the following principle: upon exposure to nuclear radiation such as cosmic rays, some of the bound electrons in
a mineral's lattice are detached from their parent nuclei and become freely mobile; they enter the conduction band. Structural defects in the lattice create localized charge deficits, which act as traps for the conduction electrons. Most electrons recombine or are briefly trapped in very shallow traps, but a few are trapped in deep traps and remain there over geological timescales (1-5000 Ma). Heat or light can eject charges from traps back into the conduction band. When an electron recombines with a luminescence centre, a photon is emitted. This phenomenon forms the basis of thermoluminescence and optical dating. Therefore, if the electrons lying in deep traps can be stimulated to recombine (e.g. with a Laser with associated precision optics), the age of the material relative to surrounding material can be derived. As bodies without atmosphere are subject to a certain degree of "gardening" their surfaces get covered over time with "regolith" which stops the trapping process in the lower layers while restarting it on the new surface. If now electron recombination is stimulated in the lower layers the age of these layers can be determined. Thus the relative age of the surface material of an airless body can be determined by remote sensing from orbit. The measurements would as a side product also provide information on the composition of the material with respect to surface geological features and the degree of gardening that has occurred within the regolith.
**Reference:**


Constraints from isotopic compositions of meteorites: I. Asteroid origins and the early evolution of the asteroid belt

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Abstract

Evidence for two disk reservoirs: Subtle variations in the isotopes of Cr, Ti, Ni, Mo and O show that every meteorite falls into one or other of two well-resolved classes dubbed, carbonaceous and non-carbonaceous [1-4]. The carbonaceous class (CC) is dominated by carbonaceous chondrites (cosmic sediments) and the non-carbonaceous class (NC) by ordinary chondrites but each class also includes meteorites whose parent bodies melted (irons, stony irons and basaltic meteorites). Earth and Mars fall in the non-carbonaceous class. The two classes imply two separate reservoirs of disk material which must have been spatially separated throughout the period when the meteorite parent bodies were accreting, i.e. from <0.5 Myr to >3.5 Myr after the formation of calcium-aluminum-rich inclusions (CAIs) [3, 7].
CAIs are refractory granules whose age is taken to define $t_0$ for the solar system. It seems likely that the two reservoirs were isolated by a gap in the disk opened by proto-Jupiter at $\sim 0.5 \text{ Myr}$ after CAIs, with the non-carbonaceous class inside Jupiter’s orbit and the carbonaceous class beyond it [3-6]. Such gaps are a feature of the stunning images of protostellar disks observed by ALMA which are thought to be caused by planet growth [8].

Formation of the asteroid belt: Carbonaceous and ordinary chondrites are derived from C type and S type asteroids, respectively [9]. Thus, C type asteroids formed beyond Jupiter and were scattered into the belt $> \sim 3.5 \text{ Myr}$ after CAIs. This interpretation rules out the classical model in which asteroids accreted between Mars and Jupiter and were later depleted by resonances with Jupiter and protoplanets [10]. It also helps to explain why the belt is dominated by two types of asteroids, C and S, which have distinctly different spectral reflectance, albedos, and water contents [11, 12].

How, then, was the asteroid belt assembled? Scattering of C types by Jupiter and scattering of S types by terrestrial planets into an empty belt [13] seems unlikely as isotopic evidence suggests that enstatite chondrites and achondrites and hence E type asteroids accreted inside $\sim 1.3 \text{ AU}$ [9, 19]. Scattering of C types by Jupiter into a low-mass belt of S types [14] would satisfy the isotopic constraints but it requires a fortuitous
match in their masses. We prefer the Grand Tack model in which Jupiter migrated inwards, emptying the belt, then migrated outwards, repopulating it with scattered C types from beyond Jupiter and indigenous S types [15, 16]. This model fits the abundances and distributions of C and S types [15] and with the giant impacts inferred for CB chondrites [17] and ureilites at ~5 Myr after CAIs [6, 18] when the two classes were intermixed.

Reference:


[16] Sanders I. S. et al. This workshop.


Numerical simulations of the impact forming the Hygiea family

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Abstract

Hygiea family has been formed by a giant impact approx. 2Gyr ago (Carruba et al. 2014). While the total mass of the family members constitutes about 1.7% of the mass of (10) Hygiea, this event was one of the most energetic impacts in the history of the Main belt. To get a better understanding of this family-forming event, we performed a number of collisional simulations, using a newly developed SPH/N-body code. The code includes self-gravity and thus allows to simulate fragmentation and substantial part of the reaccumulation process.

We found that simulations can produce a good fit to the observed SFD. We analyzed the ejection velocities and spatial distribution of the fragments and estimated the most probable size of the impactor and the impact angle. While the slope of the SFD shows little dependence on impact angle, the head-on impacts tend to create one or several intermediate-sized bodies; the oblique impacts form none. We further
determined the original position of the fragments in the parent body and compared the resulting largest remnants when different rheological models are used in the simulations, namely the von Mises yield criterion and the constitutive model of Collins et al. (2004).

Reference:

More on properties of retrograde 1:1 mean motion resonance

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Abstract

Most of objects in the Solar system move around the Sun in the anticlockwise manner when seen from above the north ecliptic pole. And only a small number of celestial bodies move in opposite direction [1,2]. Similar to prograde motion, the retrograde motion of a celestial body can also be in resonance with one of the major planets. For example, the asteroid 2015 BZ509 is in retrograde 1:1 mean motion resonance with Jupiter [3]. Theoretical studies demonstrated that such resonance can prevent collision of asteroid and planet in the case of co-orbital motion [4,5]. The aim of our investigation is to obtain more information about the properties of this resonance.

As in other MMR three dynamical processes can be distinguished in the case under consideration: "fast" process corresponds to planet and asteroid motions in orbit, "semi-fast" process is variation of the resonance argument (which describes the relative position of the planet and the asteroid
in their orbital motions), and, finally, "slow" process is the secular evolution of the orbit shape (characterized by the eccentricity) and orientation (which depends on the ascending node longitude, inclination and argument of pericenter).

With the use of double numerical averaging we construct evolutionary equations that describe the long-term behaviour of asteroid's orbital elements (the “slow” process). Special attention is paid to possible transitions between different types of orbits existing at retrograde 1:1 resonance.

The author acknowledges the financial support from the Presidium of the Russian Academy of Sciences under the scope of the Program 28 "Space: investigations of the fundamental processes and their interrelationships”

Reference:


The Size-Frequency Distribution of Planetesimals: Results from Numerical Simulations

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Abstract

A primary diagnostic for constraining planetesimal formation mechanisms lies within the size-frequency distribution of planetesimals. In this talk, I will describe current efforts to generate predictions of this size-frequency distribution from numerical calculations of planetesimal formation. The streaming instability model for planetesimal formation is currently one of the more favored models, and as such, I will present the results of planetesimal sizes and size-frequency distributions extracted from simulations of this process. I will then compare these results with the distribution of Main Belt asteroids and discuss the implications for asteroid formation. I will conclude with an outlook for future studies of planetesimal formation.

Reference:
N/A
Since the arrival at asteroid Ryugu on June 27, 2019, Hayabusa2 has conducted a variety of remote sensing observations. The observations have revealed that Ryugu is Cb-type spectra, consistent with both Eulalia and Polana families, the most dispersed C-type families in the inner main belt. Also, its very low albedo (4.5±0.2%) is much darker than most carbonaceous chondrites, such as CM and CI, but rather similar to thermally metamorphosed carbonaceous chondrites [1].

After several months of observations and multiple rehearsal descent operations, Hayabusa2 made a successful touchdown for sampling on Feb. 22, 2019. The sampling site is called L01E near the equator. It is one of the flattest areas on Ryugu, which has extremely high density of boulders. Ryugu’s spectral properties are very homogeneous over the globe, but the surface materials appear to contain a variety of materials perhaps from different parts of the parent body. The high
homogeneity is likely resulting from high degree of mixing. Thus, the obtained samples may contain many components on asteroid Ryugu.

Furthermore, the touchdown operations have caused very dynamic phenomena on its surface, lifting up many pebbles to very high altitudes. Significant color change was also observed on the disturbed surface, which will help us understand the properties of space weathering on such a dark asteroids.

Finally, a short summary of sample analysis of Itokawa is given to discuss about the outlook of Hayabusa2 sample analysis.

Reference:
Hayabusa2 observations reveals Ryugu’s parent body properties

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Abstract

JAXA’s Hayabusa2 spacecraft arrived at asteroid Ryugu on June 27, 2018 and succeeded the first touchdown on its surface for sampling on Feb. 22, 2019. It is still conducting a variety of remote sensing observations.
The global observations of Ryugu have revealed that it has Cb-type spectra without a strong 0.7-μm absorption band and with a very low 0.55-μm geometric albedo (4.5+/−0.2)% among the lowest in the solar system. Its crater retention age for small craters (~10 m) is very young (< a few Myr), supporting a high surface rejuvenation rate.

The Cb-type spectral is consistent with the dynamically most probable source asteroid families for Ryugu: Eulalia and Polana families. These families are among the most widely dispersed C-complex families in the inner main belt, allowing to deliver family members at very high flux rate to the resonance zones (nue6 and 3:1) at both inner and outer boundaries of the inner main belt, which are the dominant source of near-Earth objects (NEOs).

Furthermore, very high abundance (about twice Itokawa) of boulders are found on Ryugu. Ryugu’s surface is mechanically unconsolidated, allowing surface boulders to move easily. These two properties suggest that large mass of boulders and pebbles can be ejected from Ryugu to space over time. In fact, interaction between Hayabusa2 spacecraft and the Ryugu surface during the touchdown operations have lifted up a large number of pebbles to high altitudes.

Thus, a large number of macroscopic objects of Ryugu-like materials may enter Earth’s atmosphere, implying that there should be counterparts in our meteorite collection. One of
such candidates is moderately dehydrated carbonaceous chondrites, which exhibit very low albedo and flat spectra. They are also found with high abundance in Antarctica, which has sampled the long-term average flux of infalling meteorites on Earth. Another is interplanetary dust particles (IDPs), which also exhibit low albedos and account for large influx of extraterrestrial material to Earth. Although a decisive conclusion may not be obtained before the analysis of Ryugu samples returned to Earth, currently available observational evidence, such as high boulder abundance on Ryugu, favors that its composition may be similar to moderately dehydrated carbonaceous chondrites. This would further suggest that Ryugu’s relatively low abundance of hydrated minerals may be due to partial dehydration on Ryugu’s parent body.

Reference:


Exploring the Main Belt with Gaia

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Abstract

The Gaia mission of ESA is obtaining extremely accurate astrometry and spectro-photometry of all sources brighter than G~20, including around 350,000 minor bodies. In the frame of the second data release, in April 2018, the observations of a first sample of 14,000 asteroids have been published [1]. For the first time, accurate astrometry at sub-mas (milli-arcsec) level has become available. Such performance is better than the accuracy of radar measurements, the best available in the archives but limited to a very small number of positions, mainly of near-Earth objects only.

At this level, the astrometric signal becomes strongly sensitive to subtle perturbations, such as Yarkovsky, for a number of targets much larger than before. We investigated such features within the DR2 data and we are now capable to show that, for the first time, we can reach the detection of the Yarkovsky drift directly in the Main Belt [2]. As a consequence, we are now able to directly probe asteroid families to search
for drift measurements of their members. These can be applied to derive improved family ages [3].

Such perspectives come with serious challenges. The most important is the joint exploitation of Gaia astrometry with ground-based data, that have been mostly reduced with pre-Gaia catalogs. Zonal biases, absent or inaccurate proper motions, and differences in the reference systems, introduce errors that have to be corrected for practical use. We have set up an accurate de-biasing of zonal errors to mitigate this issue, by using DR2 as a reference catalog. With respect to previous approaches [4], we do not compute corrections for catalogs, but for single positions extracted at the Minor Planet Center. Our successful application to Yarkovsky measurements shows that the approach is effective and flexible, potentially capable of taking into account several specific properties of past surveys.

Improved orbits are also greatly enhancing the success rate of stellar occultations, that can be used to improve our knowledge of asteroid diameters and shapes in the Main Belt, in synergy with other techniques.

Eventually we stress that, with ~10 times more asteroids and a longer time span, the next data release of Gaia will permit a large scale application of the methods mentioned above. The availability of reflectance spectra will also add a further
dimension to the data, effectively expanding the currently available sample of physical properties.

**Reference:**


Inclination excitation in the asteroid belt during the evaporation of the protoplanetary disc

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Abstract

We study inclination excitation in the asteroid belt and the inner solar system, during the evaporation of the protoplanetary gas disk. We assume a model of the early solar system, in which the giant planets reside in a resonant configuration, consistent with recent evolution models (e.g. 'Nice model', [1]-[2]), while the disk's gravity is felt by planets, terrestrial planet embryos and 'asteroids'. The disk is set to evaporate, either uniformly or following recent photo-evaporation models. All bodies have their secular frequencies modified by the disk's changing gravity, while embryos are also allowed to undergo Type I migration. We performed several simulations, assuming different settings; our parametric study is presented. Despite the fact that different simulations have different degrees of success in reproducing the desired dynamical features of the present-day system, our simulations do show a generic outcome: (a) at least part of the asteroid belt region is excited in inclination to an amount
consistent with the present-day distribution, due to the combined action of scattering by embryos ([3]-[4]) and secular resonance sweeping, and (b) embryos can efficiently evacuate the asteroid belt and accumulate in the terrestrial planets region, which could eventually lead to the formation of a system, reasonably similar to the observed one. The initial conditions and assumptions that best match both observational constraints are discussed.

Reference:


Global temperature maps of Vesta and Ceres from Dawn/VIR

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Abstract

We present a summary of the thermal maps obtained by the NASA Dawn mission [1] during the orbital phases around the large asteroid Vesta in the period 2011-2012 and around the dwarf planet Ceres in the period 2015-2018.

The Visible InfraRed mapping spectrometer (VIR) onboard Dawn [2] operates in the overall spectral range 0.25-5.1 μm, with the main goal of identifying and mapping the mineralogy
of the target in its uppermost layer, as thick as several tens of microns.

Taking advantage of the 3-5 µm wavelength range, where the thermal radiation emitted from the dayside is easily revealed in the reflectance spectra, it is possible to use VIR as a thermal mapper, i.e. as a tool to derive spatially-resolved temperature images and maps. To achieve this goal, we rely on a Bayesian approach to nonlinear inversion that allows simultaneous retrieval of surface temperature and emissivity for each spectrum acquired by VIR. In this way, thermal maps were obtained for several orbit phases (carried out at different altitudes over the surface implying variable spatial resolutions) and in different bins of local solar times. These maps also allow a detailed investigation of the thermal behaviour of specific regions of interest seen at the local scale. Such investigations fall within the broader science goal of shedding light into the physical properties of the surface of Vesta and Ceres, and are complementary to mineralogical investigations carried out at shorter wavelengths.

The lowest temperature value measurable by VIR is dictated by the in-flight instrumental noise and is close to 170 K on an average, meaning that VIR is not sensitive to nighttime temperatures and - given the generally low thermal inertia - cannot retrieve temperatures for regions that underwent shadowing for time periods longer than several minutes.
At low latitudes, on Vesta the maximum daytime temperatures reach 275 K, while on Ceres the maximum values are as large as 245 K (higher values are actually found in high-resolution data). For a given latitude and insolation, this is the result of the thermophysical properties of the uppermost surface layer sensed by VIR at a given heliocentric distance. However, seasonal changes in surface temperature for a specific location are seen to occur on Vesta over a one-year period [3], which are hardly spotted on Ceres over even longer periods. This is due to the small obliquity of Ceres combined with the relatively small eccentricity of its orbit.

Reference:


Secular resonance sweeping in the early solar system (revisited)

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Abstract

We revisit the problem of secular resonance sweeping through the inner solar system, during its early phases of evolution, when the protoplanetary gas disc is still present. We develop a semi-numerical method to compute the secular frequencies and their time evolution, during the (uniform or not) decay of the disk, for the system of giant planets and for planetesimals, spread out from 0.3 to 4 AU. Our results explain why, in older studies ([1]-[2]), no inclination excitation was observed, as no inclination resonance can sweep through the asteroid belt region, when Jupiter and Saturn are assumed to follow their current orbits (or similar). On the contrary, for different initial planetary configurations, consistent with recent evolution models (i.e. 'Nice model'-like resonant systems, [3]-[4]), the s=s6 resonance can sweep through parts or even the entire asteroid belt, providing a significant amount of inclination excitation, which however depends on the adopted planetary configuration, the disk evaporation mode
and time-scale, and the presence or not of mild chaos in the planetary orbits [5]; a parametric study is presented. Independently of the specifics under which our model can describe the inclination distribution of the present-day asteroid belt, our results suggest that the secular sweeping phenomenon cannot be neglected, if we assume that the giant planets indeed resided on different orbits than their present ones, at those epochs.

Reference:


Discovery of a young subfamily of the (221) Eos asteroid family

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Abstract

We report the discovery of a young cluster of asteroids that originated by the breakup of an asteroid member of the (221) Eos family. By applying the Hierarchical clustering method to the catalogue of proper elements we have identified 26 members of this new small group of asteroids. We have established that the statistical significance of this cluster is >99 per cent; therefore it corresponds to a real asteroid family, named the (633) Zelima cluster, after its lowest numbered member. The orbits of its members are dynamically stable, a fact that enabled us to use the backward integration method, in two variants to identify potential interlopers and estimate its age. Applying it first on the orbits of the nominal family members we identified three asteroids as interlopers. Then we applied it on a set of statistically equivalent orbital and physical clones of each member to determine the age of the cluster, with a result of 2.9 ± 0.2 Myr.
Reference:
First Results from NASA's OSIRIS-REx Space Mission

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Abstract

We report on scientific results of NASA's OSIRIS-REx sample return mission that is visiting the B-type near-Earth asteroid (101955) Bennu. The spacecraft launched in September 2016, arrived at Bennu in December 2018 and will survey and study the asteroid until collecting a sample in the summer of 2020 and return it to Earth in 2023. The target asteroid Bennu has so far met expectations in many regards, giving credit to the extensive astronomical campaign to characterize its properties. It has a spinning-top shape, with the mass, density, full-disk thermal inertia and spectral properties largely similar to what was estimated before arrival. It has, of course, surprised in some ways. It is littered with large boulders and lacks any large regolith ponds, which is surprising given its thermal inertia. It also has some large craters along its equator, which suggests an older surface, despite being small enough to have a rapid YORP-spinup timescale. Finally, it has a
wide diversity of boulder morphologies that point to both a range of fundamental properties and ongoing processing.

**Reference:**
n/a
The Themis Family

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Abstract

The Themis family is notable for numerous very large prospective family members, and for having family members that appear to be activated. Themis itself is notable for the detection of water ice on its surface. Here we examine this large and old family using the V-shape asteroid family characterization tool, and report on its properties - especially where they differ from those measured by the Hierarchical Clustering Method (HCM) that is typically used.

Reference:
-
A comparative study of size frequency distributions of Jupiter Trojans, Hildas and Main Belt Asteroids: A clue to planet migration history

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\textsuperscript{4}Kindai University  
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Abstract

We performed a comparative study of SFDs for each group of small bodies in an attempt to obtain clues about planet migration that affected those populations\cite{1}.

We have obtained size frequency distributions (SFDs) of main belt asteroids (MBAs), Hildas, and Jupiter Trojans (JTs) by using the 8.2-m Subaru telescope equipped with the wide-field CCD cameras: Suprime-Cam (SC) or Hyper Suprime-Cam (HSC) since 2002\cite{2-7}. The combination of Subaru telescope and the wide field of view of SC or HSC is the best instrument to detect small moving objects. It can detect objects up to
apparent magnitudes 24.4 – 24.5 mag (Rc-band), which corresponds to sub–km in diameter for MBAs and about 1 km for Hildas and JTs. We combined these SFDs obtained from our surveys with those derived from literature to obtain the individual representative SFD for MBAs, Hildas and JTs in the size range of sub–km to 1000 km.

We found that the SFDs of JTs and Hildas are roughly flat in the R–plot, while that of MBAs has a wavy structure. We also investigated the SFDs in the inner, middle, and outer regions of the main belt. We found that the shape of the SFDs changes gradually with increasing heliocentric distance across these regions. This trend continues beyond the outer region, where the SFD becomes flatter as shown by the SFDs of JTs and Hildas. Recent planet migration models suggest that the current JTs originated in the trans-Neptunian region and were captured as Trojans during planet migration. The finding of a gradual change of the SFDs from the inner MBAs to JTs is in line with the idea that trans-Neptunian objects were implanted not only into the JT region, but also into the Hildas and outer main belt region during the planet migration.

In order to investigate this, we considered a synthetic population of TNO assuming with a SFD represented by a power law distribution of \( N(> D) \propto D^{-3} \) (estimated from crater's SFD of Pluto and Charon). We then added this synthetic population to the MBA populations in various
proportions. As a result, we show that the higher the proportion, the flatter the wavy SFD of MBAs becomes. It is consistent with the trend inferred from the above implantation hypothesis.

Reference:


Observational campaign of DESTINY+ mission targets: (3200) Phaethon and (155140) 2005UD in 2017-2018

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Abstract

DESTINY+ (Demonstration and Experiment of Space Technology for Interplanetary voyages, Phaethon flyby and Dust Science) was selected for JAXA/ISAS Epsilon class small program with a launch targeted for 2022. It is a joint mission of technology demonstration and scientific observation to demonstrate high performance electric propelled vehicle technology and high-speed flyby exploration of asteroid(s). DESTINY+ spacecraft is injected into an elliptical orbit around the Earth, then raise the orbit to reach the moon. After multiple lunar gravity assists, it heads for Phaethon[1].
During the cruising phase, the spacecraft investigates the dust along its trajectory. Interplanetary and interstellar dust will be detected and analyzed in-situ by the dust analyzer (DDA)[2].

During the flyby phase (relative velocity with Phaethon is 33km/s), two sets of camera: Telescopic Camera (TCAP) and Multiband Camera (MCAP)(400, 480, 550, 700, 850, 950 nm)) take image of Phaethon[3]. The surface of Phaethon can be viewed with a spatial resolution of less than 5m per pixel by TCAP during the closest flyby around 500 km distant from Phaethon. The DDA may detect dust particles from Phaethon. Recent numerical simulation suggests 10 dust particles or more can be detected during flyby at the distance of 500 km from Phaethon[4].

After the flyby, DESTINY+ may head for another asteroid such as 2005 UD, a possible breakup body of Phaethon, as an extended mission.

We (DESTINY+ Team) called for a series of dense observations of Phaethon and 2005UD in 2017-2018. More than 100 researchers were responded in the world[5]. By numerous observations with different methods, so far, rotation period, average colors, absolute magnitudes, reflectance spectra, 0.4-4.2 um for Phaethon and 0.4-2.5um for 2005UD[6] were obtained during this observation campaign. Radar observation was done for Phaethon. Polarimetric observations were done for both asteroids. As preliminary results, the following
properties were reported. Rotation periods: 5.2 hr (or 7.85 hr) for 2005UD, 3.6 hr for Phaethon. Average colors: B-V=0.71, V-R=0.37, V-I=0.32 for 2005UD, B-V=0.73, V-R=0.36 for Phaethon. Absolute magnitude is 17.25 mag for 2005UD. Interestingly, the reported NIR-spectra of Phaethon and 2005UD were totally different: concave-up and blue for Phaethon, linear and red for 2005UD. Both asteroids have very similar polarimetric properties. Lightcurve observations revealed Phaethon has a top shape. Radar observation estimated the Phaethon's diameter is about 6 km, and revealed no coma, no satellite. Multiple surface features, including concavity of >1 km across were discovered by the radar observation.

Reference:


Spectral analysis of the surface of Vesta in the wavelength range 2.5 - 5.0 µm

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Abstract

Vesta, the largest asteroid in the Main Asteroid Belt, was the first target of the NASA Dawn mission [1]. During its close exploration of Vesta in 2011-2012, the Visible InfraRed mapping spectrometer (VIR) onboard Dawn [2] acquired a large amount of hyperspectral images, achieving nearly global coverage at varying spatial scales. Since the early 1970s,
ground-based telescopic observations revealed that the surface of Vesta is globally dominated by pyroxenes [3], which were later associated to the Howardite-Eucrite-Diogenite (HED) family of meteorites [4].

VIR was equipped with two channels, the visible and the infrared, spanning the overall wavelength range between 0.25 and 5.1 µm [2]. All Vesta spectra acquired by VIR are dominated by two strong absorption bands centered at about 0.9 and 1.9 µm, due to Fe2+ in pyroxenes [5]. VIR data allowed for producing the first mineralogical maps of Vesta at an unprecedented spatial resolution (up to ~50 meters/pixel). The most widespread lithology is howardite rich-eucrite, while diogenite has been observed mainly in the Rheasilvia impact basin located at the South Pole and at higher latitudes, matching the ejecta of Rheasilvia [5, 6]. At the local scale, several geologic features are observed: high-albedo material units revealing fresh endogenous material [7], OH-rich material, which likely has been delivered on Vesta by low-albedo (probably carbonaceous) asteroids over time [8, 9], olivine-rich areas in about ten craters, most notably Bellicia and Arruntia [10], and spectrally distinct (reddish) ejecta in the Oppia and Octavia craters.

The mineralogical analysis of Vesta surface carried out so far by means of VIR data, relied on the spectral range between 0.5 and 2.5 µm. The infrared spectral region between 3 and 5
μm is increasingly affected by the thermal emission on the dayside of the asteroid, masking potential absorption features diagnostic of still-unidentified mineral species. Here, we analyze the wavelength range 2.5-5.1 μm after applying a suitable thermal removal with the aim of detecting the possible presence of previously undisclosed absorption bands. This study and the comparison with appropriate laboratory analogues can improve our knowledge of the surface composition of Vesta, allowing for a better characterization of its pyroxenes and/or emphasizing the presence of new species.

Reference:
[1] Russell et al., 2011, PSS.
[2] De Sanctis et al., 2011, PSS.