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How much prebiotic material is out there?

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Abstract. The so-called "primitive" small bodies of the solar system have formed in the water- and organic-rich outer regions of the protoplanetary disk, and they are considered as the most probable source of terrestrial prebiotic material. To constrain their role and efficiency in such delivery, we need i) space missions to study in unprecedented detail primitive targets and their returned samples, and ii) ground-based surveys characterising the whole small body population to better quantify how much of prebiotic material these objects could have brought to the primordial Earth. Besides being involved in Hayabusa2 and OSIRIS-REx sample return space missions, our team is currently leading the H2020 NEOROCKS project, whose main goal is the dynamical and physical characterisation of the near-Earth asteroid population. Here we present our activity and future plans, with a specific focus on the determination of the abundancy of primitive asteroids at different size scales.

Key words. Astrobiology – Minor planets, asteroids: general

1. Introduction

Asteroids and comets that have formed in the outer regions of the solar system protoplanetary disk are commonly referred as "primitive" small bodies. They have long been considered as an important source of terrestrial prebiotic material, through the delivery of water and organic compounds to the dry, primordial Earth. However, comparative measurements of the D/H isotope ratio seem to exclude the hypothesis of a significant cometary contribution to the water of the Earth's oceans and atmosphere (e.g., Altwegg et al. 2015), while primitive asteroids could have played the major role in this regard. Indeed, both terrestrial nitrogen and hydrogen isotopic compositions share similar ranges of values with carbonaceous chondrite meteorites, whose parent bodies are primitive asteroids (e.g., Marty et al. 2016). Such scenario is consistent with the terrestrial enrichment of volatile-rich matter through accretion of primitive planetesimals, scattered into the inner solar system at the epoch of giant planet migrations, as proposed by recent dynamical models (e.g., O'Brien et al. 2014).

The investigation of primitive small bodies – and near-Earth asteroids (NEAs) in particular – can therefore provide crucial information on the early phases of the solar system, and on the emergence of life on Earth. The Planetary Science group at INAF-OAR is involved in the Science Teams of both of the currently ongoing sample-return space missions from primitive

NEAs, namely JAXA Hayabusa2 and NASA OSIRIS-REx. As outlined in Section 2, space missions to primitive asteroids are necessary to study in unprecedented detail selected targets and their returned samples. In parallel, we are deeply involved in ground-based surveys to characterise the global NEA population (cf. Section 3), which are fundamental to better quantify how much of prebiotic material these objects could have brought to the primordial Earth.

2. Space exploration and sample-return from NEAs

Sample-return space missions from primitive NEAs give us the unprecedented possibility to perform detailed laboratory investigations of unaltered samples – unlike carbonaceous chondrite meteorites which are altered during their atmospheric entry, or terrestrial weathering once fallen. In this way, an important ambiguity is removed in assessing the contribution of primitive small bodies to the origin and evolution of life on Earth.

In 2018-2019, Hayabusa2 orbited the primitive asteroid Ryugu and performed two separate touchdowns to collect sample materials, which have been safely returned to Earth in December 2020 through a re-entry capsule. The mission has therefore been extended and will reach in 2031 the NEA 1998 KY26, after a flyby of the NEA 2001 CC21 in 2026. OSIRIS-REx reached the primitive asteroid Bennu in December 2018 and collected samples from its surface in October 2020. Their return to Earth is planned for September 2023.

Waiting for the results that will come from the accurate laboratory analysis of the collected samples, the remote-sensing data obtained by Hayabusa2 and OSIRIS-REx already provided evidence that carbon-rich and hydrated materials are abundant and widespread over both Ryugu and Bennu (e.g., Kitazato et al. 2019; Simon et al. 2020). However, despite the many similarities shared by these two asteroids, a striking difference emerged for what concerns their surface hydration levels, with Ryugu being significantly drier than Bennu (e.g., Hamilton et al. 2019; Kitazato et al. 2021).

Such findings highlight the importance of programming further space missions to primitive asteroids, to characterize with groundbreaking detail their physical diversity (and astrobiological relevance), which may be due to parent asteroids properties and/or different evolutionary processes. However, it should be noted that current propulsion technologies make only a few tens of primitive NEAs accessible for robotic exploration (e.g., Ieva et al. 2020).

3. Ground-based studies of NEAs

Ground-based surveys are necessary to characterise the NEA population at large, investigate their composition distribution at different size scales, then better evaluate the asteroid contribution in bringing volatile- and organic-rich material to the primordial Earth.

We stress that disk-averaged spectroscopic observations from Earth observatories still have the potential to reveal important information about NEA compositional nature. For example, Perna et al. (2017) used ESO-VLT data of Ryugu to predict a relatively homogeneous surface composition, similar to unusual/heated CM and CI carbonaceous chondrites (Fig.1). Such results have been strengthened by the analysis of data from the NIRS3 spectrometer onboard Hayabusa2 (Kitazato et al. 2019), evidencing that the weak intensity of the 2.72-micron absorption feature (associated to the ubiquitous presence of hydroxyl–bearing minerals over the surface) is similar to that of thermally and/or shock-metamorphosed CM/CI chondrite meteorites.

Current NEA discoveries mainly concern small-to-tiny objects (in the 10^0-10^2 m size range) close approaching the Earth. The investigation of such small-sized NEAs – associated to higher impact frequencies – is necessary to properly evaluate the asteroidal contribution to the delivery of volatiles and organics to the early Earth. More in general, the proximity of NEAs gives us the opportunity to study the size-dependency of several asteroid physical properties. Reflectance spectroscopy is particularly useful in this sense, as it allows the taxonomic classification to be determined and provides clues about the surface composition, mineralogy and scattering properties.

Unfortunately, small NEAs become bright enough for physical characterization only for very short time spans, during their close approaches with our planet. For this reason, the fraction of NEAs with assigned taxonomic class (with respect to the known population in the same size range) drops from about $\frac{1}{3}$ for km-sized bodies to about $\frac{1}{100}$ for objects smaller than 300 m.

To reduce this deficiency, we recently performed a spectroscopic survey at ESO-NTT fully dedicated to the characterization of small, newly-discovered NEAs (Perna et al. 2018). We found a peculiar taxonomic distribution, with respect to larger NEAs, with a particular abundance of the very primitive and organic-rich D-type asteroids. In the same work we have also proposed a novel way to distinguish primitive asteroids in the X-complex (including objects of either carbonaceous, silicaceous, enstatitic, or metallic nature), by the absence of spectral reddening at increasing solar phase angles (Fig.2). In Ieva et al. (2020) we extended our survey with new TNG observations as well as literature data, for a total of 1081 NEAs under analysis. In this way, we could confirm that primitive asteroids (D-, K-, L-types) – despite their observational bias, as they present low-albedo surfaces – seem more abundant at small sizes (corresponding to larger absolute magnitudes H, cf. Fig.3).

What the above may suggest is that the asteroidal contribution to the delivery of the prebiotic material to the primitive Earth could be more important than foreseen prior of our observations. We should however keep in mind that these results are based on still limited statistics, with many taxonomic classes populated by few tens of NEAs only. More data are crucial to further test and extend such findings.

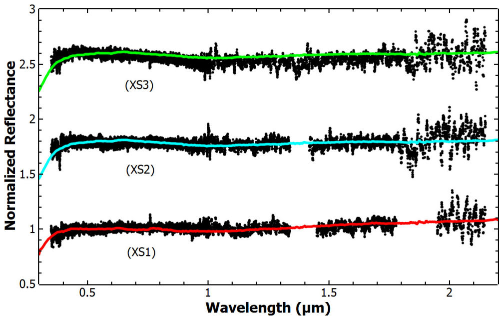

Fig. 1. VLT X-shooter reflectance spectra of Ryugu, shifted by 0.8 for clarity. Regions affected by strong atmospheric absorption have been cut out. Superimposed are the spectra of thermally altered samples of the CM carbonaceous chondrite Murchison, from the RELAB archive (Pieters & Hiroi 2004). Figure adapted from Perna et al. (2017).

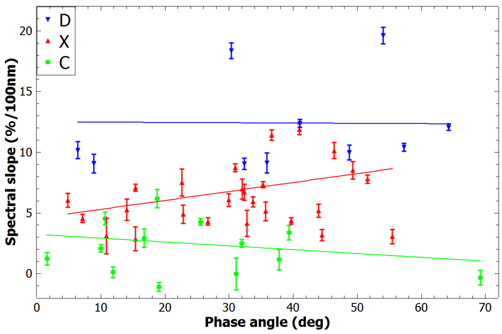

Fig. 2. Visible spectral slope vs. phase angle for D-, X- and C-type NEAs observed within our ESO-NTT survey. Linear fits are also reported. On average, low-albedo asteroids (C-complex and D-types) seem to show no phase reddening, suggesting a new way to discriminate primitive objects within the X-complex, whenever measurements are available spanning a wide range of phase angles. Figure adapted from Perna et al. (2018).

4. Future perspectives

As outlined in the previous sections, systematic and rapid-response physical observations of newly-discovered NEAs are necessary in order to not leave the characterization rate behind the discovery rate, and significantly increase the available statistics on small-sized asteroids.

This is one of the main goals of the NEOROCKS (NEO Rapid Observation, Characterization and Key Simulations) project. Started in 2020 and funded by the European Commission H2020 programme, NEOROCKS is an international project involving 14 part-

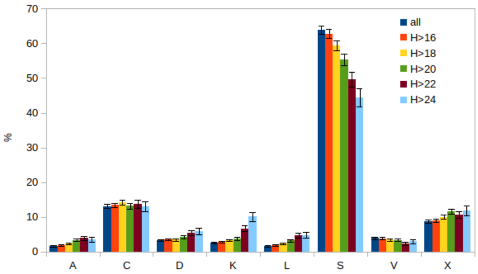

Fig. 3. Taxonomic distribution of NEAs, as a function of limiting absolute magnitude H. Error bars were computed using a standard Poisson approach. Figure adapted from Ieva et al. (2020).

ners (research institutes, universities, industries and the Italian Space Agency) from 7 European countries, coordinated by the Planetary Science team at INAF-OAR. NEOROCKS aims to improve our knowledge of the dynamical and physical properties of the NEA population, to shed light on their origin and evolution as well as for planetary defense, by improving and optimizing observational activities, enhancing modelling and simulation tasks, fostering international coordination and speeding-up response times for follow-up observations after discovery. Having guaranteed observing time and/or ease of access to large aperture telescopes for physical characterization is a major asset of the project. Innovative orbit determination techniques developed during NEOROCKS will play a fundamental role in this scenario, driving both observational activity and next space missions feasibility.

The new high quality data that will be obtained in the coming years by NEOROCKS (and further surveys) on more and more, smaller and smaller NEAs will help us to properly quantify the abundance of primitive material at the different asteroid scales. By pooling these efforts with the next laboratory experiments on Hayabusa2 and OSIRIS-REx (and hopefully further) samples, we will better understand how much prebiotic material is "out there", and its potential role in the emergence of life on Earth.

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