Potential resources on 6 Hebe asteroid

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Abstract. 6 Hebe located in the main asteroid belt is one of the potential extraterrestrial objects of future mining exploitation. It is also widely recognized as the parent body of H chondrites. Based on the chemical analyses of H chondrites, the average chemical composition of the asteroid was determined. This asteroid is composed of, among others [in Mg]: Fe (3.54 · 10¹⁵), Ni (2.17 · 10¹⁴), Cr (4.44 · 10¹³), Co (1.05 · 10¹³), Cu (1.19 · 10¹²), Mo (1.78 · 10¹⁰). These elements are a component of various minerals, including minerals that can be a future object of exploitation. Primarily, they are FeNi alloy minerals, but also e.g. chromite. The reserves of these elements are smaller, but assuming that it is 10 or even 1% of resources, they are still huge. The reserves of 6 Hebe can cover Earth’s demand for selected elements for several thousand to even several million years. For comparison, with the current mining production of iron, the earth’s resources will last 153 years, and reserves – 56 years [1]. Extraterrestrial mining may in the future be an ecological alternative to mining on Earth.

1. Introduction
The subject of extraterrestrial mining is no longer reserved for science-fiction writers and film studios in Los Angeles [2][3][4]. Numerous countries create laws regulating future extraction of raw materials outside Earth (Luxembourg in 2017, The United States in 2020). More and more private companies from the space sector (associated with people like Jeff Bezos or Elon Musk as well as small companies like ABM Space or Genoa from Poland), with the generous support of some governments, are investing billions of dollars in technologies that will enable this exploitation. It all happens for two very important reasons. First of all, Earth's resources are limited and increasingly difficult to access, which is noticed by both world leaders and representatives of the global mining industry. Although thanks to new technologies we can exploit poorer and poorer deposits and we still find new ones, more and more voices are heard about the need for regulation and more sustainable mining, which does not necessarily correspond to the real demand for raw materials. In 2010, the European Commission recognized the following metals as critical: Be, Co, Ga, Ge, Nb, Ru, Rh, Pd, In, Sb, Ta, W, Os, Ir, Pt and REE [5]. Secondly, the constant presence of human outside Earth is not possible on a larger scale (e.g. mining or residential colonies) based on the Earth's resource base.

Mining, regardless of whether we talk about it on Earth or beyond, cannot be done without geological recognition and appropriate mining equipment as well as without qualified staff. The development of appropriate equipment for the purposes of extraterrestrial mining is precisely the main goal of most research centers and private companies, and it is for this purpose that the largest money is allocated. The money put into the development of the equipment gives tangible results in the form of prototypes.
that can be presented to a wider audience and take photographs with them. However, extraterrestrial mining does not differ much from the earthly one and we should think first about what raw materials need to be extracted, where can they be found, how to get it and only knowing the real needs in the final step - to design and produce the right equipment. One of the most important tasks is linking meteorites to their parent bodies. For this, the spectral analysis of meteorites and asteroids as a tool to connect them are used. The work is carried out in numerous research centers around the world, including Université Grenoble Alpes [6], Hungarian Academy of Science, ESA [7], Mount Holyoke College in the USA and The Open University in the UK [8]. Therefore, to cover the scientific and technological gaps in exploration of extraterrestrial resources of raw materials a number of works were initiated and conducted at the Faculty of Geoengeering, Mining and Geology of the Wrocław University of Science and Technology [9][10][11][12][13].

Geological recognition is the first activity that should be performed when planning mining operations on extraterrestrial objects. Based on our earthly experience in the recognition of deposits, an unmanned mission should be sent to the appropriate asteroid to make a number of exploratory drilling. It is nearly impossible considering both required investments and available technologies. However, in the case of undifferentiated objects (such as, we are talking about meteorites, and especially chondrites), samples which reach the Earth themselves without our interference are sufficient to estimate their resources. Estimation of resources is possible due to the homogeneous distribution of minerals in the parent body. Therefore, the results of the analysis of the content of individual elements or minerals in the chondrites of a given group are similar to the actual content of these components in their parent bodies [9].

The parent bodies of meteorites are determined by the similarity of their chemical composition. In the case of meteorites, it is determined on the basis of laboratory tests, and in the case of asteroids based on the spectrum of their surface, colour or albedo. Based on these parameters, the spectral type of the asteroid is determined. Asteroids C, S and M type are most commonly observed. C type asteroids are potential parent bodies of carbonaceous chondrites Mighei type (CM), Ivuna type (CI), Renazzo type (CR), Karoonda type (CK) and possibly High-iron type (CH). S type asteroids are potential parent bodies of ordinary chondrites (H, L, LL) [14] as well as ureilites, acapulcoites, angrites, lodranites, winonaites and perhaps Rumurutiites (R) chondrites. M type asteroids are potential parent bodies of iron meteorites, mesosiderites and possibly High-iron type (CH) carbonite chondrites [15]. Other spectral types of asteroids are observed very rarely.

The most valuable information on potential raw materials may come primarily from the current and next asteroid missions. First of all, it is about the ESA - Hera and NASA - DART missions on Near Earth Asteroid 65803, which can provide us with information about its surface, including the composition of the surface [16][17][18]. Another very valuable source of information may be the CASTAway mission on the main asteroid belt [19]. In addition, the Hayabusa 2 probe should return to Earth later this year with samples of soil from 162173 Ryugu [20].

This article is one of the elements of research on extraterrestrial mining. The research carried out at Wrocław University of Science and Technology includes the determination of the extraterrestrial resource base, its catalogued and determination of methods of obtaining these raw materials. The asteroid 6 Hebe was selected for description as the first due to its size, as well as its widespread recognition as the parent body of H chondrites. However, it should be taken that the first extraterrestrial objects on which mining will be conducted will be primarily Near Earth Objects and the Moon.
2. Methods
The resources of the asteroid 6 Hebe were determined on the basis of the average chemical composition of ordinary chondrites H, according to the data provided by McSween and Huss [21], and to its mass determined on the basis of Bear et al. [22]. This asteroid is widely regarded as their parent body. Other S-type asteroids are also considered the parent bodies of the ordinary chondrites.

This type of approach to this matter seems to be legitimate because ordinary chondrites and their parent bodies are undifferentiated objects, so theoretically the distribution of components in the volume should be homogenous. It is true that volatile components may have different concentrations depending on the petrographic type, but it does not change the fact that the entire volume of the asteroid should be treated as an ore. Therefore, its average composition is given.

3. Chemical composition and potential resources on 6 Hebe asteroid
6 Hebe is an S-type asteroid and is indicated as the parent body of H group ordinary chondrites [23]. It is one of the largest objects of the main asteroid belt (Fig.1). The mass of this asteroid is estimated at $1.27 \times 10^{16}$ Mg ($\text{Mg} = 10^6 \text{ g or one metric ton}$) [22]. H chondrites, potentially originating from this particular asteroid, are already well studied. It is believed that the average elemental composition for this group of meteorites reflects sufficiently well the composition of the entire Hebe asteroid. Table 1 shows the estimated content of selected elements at 6 Hebe.

The mineral composition of the 6 Hebe asteroid is well known through the study of group H ordinary chondrites derived from it. The most important potential ore minerals are FeNi alloys: kamacite, taenite and tetrataenite. In these minerals, apart from iron and nickel, other siderophilic elements may be found, e.g. iridium, copper, germanium, cobalt, palladium, and platinum. Troilite (FeS) can also be a potential ore mineral, in which you can find chalcophile elements, e.g. copper, silver, gold, rhenium, manganese, cadmium or chromium [24]. The source of chromium can also be chromite found in chondrites.
The potential content of elements on the asteroid 6 Hebe shown in Table 1 and Figure 2 applies to its entire volume and all minerals that build this asteroid. In fact, when determining the potential resources of this facility, it should be remembered that oxygen is mainly found in silicates, which potentially will not be its source. Similarly, iron contained in silicates. The most serious source of this metal will be FeNi minerals, which contain about $1.91 \times 10^{15}$ Mg of iron on this asteroid [13]. This represents almost 54% of all iron on 6 Hebe. The next most abundant elements: silicon and magnesium do not seem to be the source of future exploitation at the moment. Like calcium, aluminum and sodium are found primarily in silicates, which are gangue minerals in terrestrial conditions. In extraterrestrial conditions, however, these minerals can also become a source of obtaining these elements due to the lack of more economical possibilities.

Table 1. The potential resources of the element on the 6 Hebe planetoid

| Element | Average resources in H ordinary chondrites [21] | Unit | Potential resources on 6 Hebe [Mg] | % | Element | Average resources in H ordinary chondrites [21] | Unit | Potential resources on 6 Hebe [Mg] |
|---------|-----------------------------------------------|------|-----------------------------------|---|---------|-----------------------------------------------|------|-----------------------------------|
| Oxygen  | 33.7                                         | ppm  | $4.53 \times 10^4$ Palladium       | 845| 1.07 $\times 10^6$ |
| Iron    | 27.2                                         | ppm  | $3.54 \times 10^3$ Osmium         | 835| 1.06 $\times 10^6$ |
| Silicon | 17.1                                         | ppm  | $2.17 \times 10^3$ Indium         | 770| 9.78 $\times 10^6$ |
| Magnesium| 14.1                                      | ppm  | $1.79 \times 10^3$ Cerium         | 763| 9.69 $\times 10^6$ |
| Sulphur | 2.0                                          | ppm  | $2.54 \times 10^4$ Neodymium      | 581| 7.38 $\times 10^6$ |
| Nickel  | 1.71                                         | ppm  | $2.17 \times 10^4$ Tellurium      | 520| 6.60 $\times 10^6$ |
| Calcium | 1.22                                         | ppm  | $1.55 \times 10^2$ Boron          | 400| 5.08 $\times 10^6$ |
| Aluminium| 1.06                                       | ppm  | $1.35 \times 10^4$ Niobium        | 400| 5.08 $\times 10^6$ |
| Sodium  | 0.61                                         | ppm  | $7.76 \times 10^3$ Lin            | 350| 4.44 $\times 10^6$ |
| Chromium| 0.35                                         | ppm  | $4.44 \times 10^3$ Dysprosium     | 305| 3.87 $\times 10^6$ |
| Manganese| 0.23                                       | ppm  | $2.97 \times 10^3$ Lanthanum      | 301| 3.82 $\times 10^6$ |
| Carbon  | 0.21                                         | ppm  | $2.67 \times 10^3$ Gadolinium     | 275| 3.49 $\times 10^6$ |
| Phosphorus| 0.12                                      | ppm  | $1.52 \times 10^2$ Lead           | 240| 3.05 $\times 10^6$ |
| Cobalt  | 0.80                                         | ppm  | $1.05 \times 10^4$ Gold           | 220| 2.79 $\times 10^6$ |
| Potassium| 0.70                                         | ppm  | $9.91 \times 10^2$ Erbium         | 213| 2.70 $\times 10^6$ |
| Titanium| 630                                          | ppm  | $8.00 \times 10^2$ Rhodium        | 210| 2.67 $\times 10^6$ |
| Chlorine| 140                                          | ppm  | $1.78 \times 10^4$ Ytterbium      | 203| 2.58 $\times 10^6$ |
| Fluorine| 125                                          | ppm  | $1.59 \times 10^2$ Samarium       | 194| 2.46 $\times 10^6$ |
| Copper  | 94                                           | ppm  | $1.19 \times 10^2$ Tungsten       | 164| 2.08 $\times 10^6$ |
| Vanadium| 73                                           | ppm  | $9.27 \times 10^2$ Hafnium        | 150| 1.90 $\times 10^6$ |
| Nitrogen| 48                                           | ppm  | $6.10 \times 10^2$ Praseodymium   | 120| 1.52 $\times 10^6$ |
| Zinc    | 47                                           | ppm  | $5.97 \times 10^2$ Rhenium        | 78 | 9.91 $\times 10^6$ |
| Germanium| 10                                          | ppm  | $1.27 \times 10^1$ Europium       | 74 | 9.40 $\times 10^6$ |
| Strontium| 8.8                                          | ppm  | $1.12 \times 10^1$ Holmium        | 74 | 9.40 $\times 10^6$ |
| Selenium| 8.0                                          | ppm  | $1.02 \times 10^1$ Antimony       | 66 | 8.38 $\times 10^6$ |
| Scandium| 7.8                                          | ppm  | $9.91 \times 10^2$ Iodine         | 60 | 7.62 $\times 10^6$ |
| Zirconium| 7.3                                         | ppm  | $9.27 \times 10^2$ Terbium        | 49 | 6.22 $\times 10^6$ |
| Gallium | 6.0                                          | ppm  | $7.62 \times 10^2$ Silver         | 45 | 5.72 $\times 10^6$ |
| Rubidium| 2.3                                          | ppm  | $2.92 \times 10^2$ Thorium        | 38 | 4.83 $\times 10^6$ |
| Arsenic | 2.2                                          | ppm  | $2.79 \times 10^2$ Thallium       | 33 | 4.19 $\times 10^6$ |
| Yttrium | 2.0                                          | ppm  | $2.54 \times 10^2$ Lutetium       | 33 | 4.19 $\times 10^6$ |
| Lithium | 1.7                                          | ppm  | $2.16 \times 10^2$ Beryllium      | 30 | 3.81 $\times 10^6$ |
| Platinum| 1.58                                         | ppm  | $2.01 \times 10^2$ Tantalum       | 21 | 2.67 $\times 10^6$ |
| Molybdenum| 1.4                                        | ppm  | $1.78 \times 10^2$ Uranium        | 13 | 1.65 $\times 10^6$ |
| Ruthenium| 1.1                                         | ppm  | $1.40 \times 10^2$ Barium         | 4.4| 5.59 $\times 10^6$ |

Table 2 presents a summary of the size of prediction resources of selected elements on the 6 Hebe asteroid with their current terrestrial mining production. A very simplified forecast of the depletion of these elements was also presented only on the assumption of constant exploitation of the entire volume of the asteroid corresponding to the current terrestrial mining production. However, even assuming very little possibility of obtaining these raw materials by extraction, processing, and transportation at the level of 1% of its resources, the asteroid is still able to satisfy the Earth's demand for a very long time. However, the actual degree of use of raw materials will depend on the demand for specific raw materials, both on Earth and on site, and on the possibility of obtaining specific elements from their minerals.
Figure 2. Elemental composition of the 6 Hebe asteroid

Table 2. Potential exploitation lifetime of selected elements on 6 Hebe

| Element     | Potential resources on 6 Hebe [Mg] | Annual mining production on Earth [1] [Mg] | Potential exploitation lifetime [years] |
|-------------|-----------------------------------|-------------------------------------------|----------------------------------------|
| Iron        | 4.53 · 10^{15}                    | 1.5 · 10^9                                | 3 020 000                              |
| Nickel      | 2.17 · 10^{14}                    | 2.3 · 10^8                                | 94 347 826                             |
| Chromium    | 4.44 · 10^{13}                    | 3.6 · 10^7                                | 1 233 333                              |
| Manganese   | 2.97 · 10^{13}                    | 1.8 · 10^7                                | 1 650 000                              |
| Cobalt      | 1.05 · 10^{13}                    | 1.4 · 10^4                                | 75 000 000                             |
| Copper      | 1.19 · 10^{12}                    | 2.1 · 10^7                                | 56 667                                 |
| Vanadium    | 9.27 · 10^{11}                    | 7.3 · 10^4                                | 12 698 630                             |
| Lithium     | 2.16 · 10^{10}                    | 8.5 · 10^4                                | 254 118                                |
| Platinum    | 2.01 · 10^{10}                    | 1.6 · 10^2                                | 125 625 000                            |
| Molybdenum  | 1.78 · 10^{10}                    | 3.0 · 10^3                                | 59 333                                 |
| Gold        | 2.79 · 10^9                      | 3.26 · 10^3                               | 855 828                                |
| Rhenium     | 9.91 · 10^8                      | 4.9 · 10^1                                | 20 224 490                             |

Table 3 presents the average enrichment of 6 Hebe in a given element in relation to the average content in the Earth's crust. However, very high enrichment does not automatically mean that it is a good source of these elements. On Earth, most of the necessary elements are concentrated in deposits. In this asteroid the components are distributed homogenous throughout its volume. For elements that occur in smaller amounts (volatile elements), e.g. copper [25][26], the petrographic type is also important. The most illustrative indicator for comparisons would be the cut-off grade, however, this indicator is characteristic for a given mine and surrounding conditions, not for the element. Due to the completely different conditions of potential exploitation on the 6 Hebe body, and possibly a completely different mining purpose, such a comparison could lead to erroneous conclusions about the profitability of the project.
### Table 3. Average enrichment of 6 Hebe in a given elements in relation to the average content in the Earth's crust [27]

| Element   | 6 Hebe | Element   | 6 Hebe |
|-----------|--------|-----------|--------|
| Osmium    | 16 700 | Sulphur   | 28,7   |
| Iridium   | 15 400 | Chromium  | 27,8   |
| Ruthenium | 11 000 | Germanium | 7,14   |
| Rhodium   | 3 500  | Magnesium | 6,41   |
| Palladium | 2 112  | Iron      | 6,30   |
| Platinum  | 395    | Copper    | 3,76   |
| Nickel    | 305    | Manganese | 3,27   |
| Rhenium   | 195    | Phosphorus| 1,59   |
| Tellurium | 104    | Arsenium  | 1,29   |
| Gold      | 88,0   | Molybdenum| 1,27   |
| Selenium  | 67,7   | Carbon    | 1,06   |
| Cobalt    | 34,6   | Bromine   | 1,00   |

### 4. Conclusions
The study of the elemental and mineral composition of meteorites falling on Earth provides the basis for determining the potential resources of extraterrestrial objects. The size of these resources is determined with the greatest accuracy for undifferentiated objects - parent asteroids of chondrites. This is due to the homogeneous distribution of ingredients in the rock and the large number of studied chondrites that are found each year on Earth.

Asteroid 6 Hebe, which is the likely parent body of H ordinary chondrites, can be a valuable source of almost all elements. This is important both because of the future need to eliminate shortages of some resources on Earth and to cover the demand for individual resources at the place of extraction. Even silicates, which build gangue minerals from our current perspective, can be a valuable source of some elements, e.g. magnesium, sodium or potassium, which in terrestrial conditions are obtained rather from the salts of these elements and are not found on asteroids in elevated concentration.

Asteroid 6 Hebe is located in the main asteroid belt, which means that it is much further away from the Moon or Mars for which manned missions are planned. However, 6 Hebe is only one of the potential parent bodies of H chondrites. At a short distance from the Earth there are many small objects (so-called NEO), which will probably be the first asteroids on which mining activities will begin. These include asteroids: (16960) 1998 QS52, (138524) 2000 OJ8 and (159857) 2004 LJ [28].

The potential exploitation of extraterrestrial resources, although seem problematic at the moment and very distant in time, may soon find significant allies in the form of ecologists and Western governments supporting environmental protection together with technological development and involvement of private companies in the space business. Moving mining production with all possible accompanying processing operations outside the Earth will significantly reduce the degradation of the natural environment and its pollution on Earth, as well as contribute to the reduction of greenhouse gas emissions.

The potential resources of the 6 Hebe asteroid, even assuming a very low utilization rate of 1%, are able to secure the Earth's demand for these resources for the next hundreds, thousands and tens of thousands of years for specific elements and its future need. In addition, this asteroid is probably able to provide all the raw materials needed to produce the necessary tools or even machine components in situ for its mining.
References

[1] U.S. Geological Survey 2019 Mineral commodity summaries 2019, U.S. Geological Survey, Reston, Virginia

[2] Graps AL, Blondel P, Bonin G, Britt D, Centouri S, Delbo M, Drube L, Duffard R, Elvis M, Faber D, Frank E, Galache JL, Green SF, Thimo Grundmann J, Hsieh H, Kereszturi A, Laine P, Levasseur-Regourd AC, Maier P, Metzger P, Michel P, Mueller M, Mueller T, Murdoch N, Parker A, Pravec P, Reddy V, Serce J, Rivkin A, Snodgrass C, Tanga P 2016 ASIME 2016 White Paper: In-Space Utilisation of Asteroids: “Answers to Questions from the Asteroid Miners”. White Paper from the Asteroid Science Intersections with In-Space Mine Engineering (ASIME) 2016 conference on September 21-22, 2016 in Luxembourg City

[3] Graps AL, Abbud-Madrid A, Abell P, Barucci A, Beck P, Bonal L, Bonin G, Risan Borgersen Ø, Britt D, Campins H, Cannon K, Carnelli I, Carry B, Crawford I, de Leon J, Drube L, Donaldson Hanna K, Elvis M, Fitzsimmons A, Galache JL, Green SF, Thimo Grundmann J, Herique A, Hestroffer D, Hsieh H, Kereszturi A, Kueppers M, Lewicki C, Lin Y, Mainzer A, Michel P, Moon HK, Nahamura T, Penttila A, Pursiainen S, Raymond C, Reddy V, Rivkin A, Serce J, Stickle A, Tanga P, Takala M, Wirtz T, Wu Y 2019 ASIME 2018 White Paper: In-Space Utilisation of Asteroids: Asteroid Composition – Answers to Questions from the Asteroid Miners. the ASIME 2018: Asteroid Intersections with Mine Engineering, Luxembourg. April 16-17, 2018.

[4] Probst A, Nitzl C, Kraus F, Förstner R 2020 Cost estimation of an asteroid mining mission using partial least squares structural equation modelling (PLS-SEM). Acta Astronautica 167 440-454

[5] Wäger PA 2011 Scarce metals – Applications, supply risks and need for action. Notizie di Politeia 104 57-66

[6] Eschrig J, Bonal L, Beck P, Prestgard TJ 2021 Spectral reflectance analysis of type 3 carbonaceous chondrites and search for their asteroidal parent bodies. Icarus 354

[7] Skulteti A, Kereszturi A, Kereszty Zs, Pal B, Szabo M, Cipriani F 2020 Role of spectral resolution for infrared asteroid compositional analysis using meteorite spectra. Acta Monthly Notices of the Royal Astronomical Society 496(1) 689-694

[8] Greenwood RC, Burbine TH, Franchi IA 2020 Linking asteroids and meteorites to the primordial planetesimal population. Geochimica et Cosmochimica Acta 277 377-406

[9] Łuszczek K, Przylibski T 2011 Skład chondrytów zwyczajnych a potencjalne surowce pasa planetoid (in Polish). Acta Societatis Metheoriticae Polonorum 2 92-111

[10] Łuszczek K, Przylibski T 2019 Potential deposits of selected metallic resources on L chondrite parent bodies. Planetary and Space Science 168 40-51

[11] Przylibski T, Donhefner H, Łuszczek K 2012 Ciała macierzyste meteorytów żelaznych jako złoża metali (in Polish). Acta Societatis Metheoriticae Polonorum 3 71-93

[12] Łuszczek K 2018 Potential importance of metallic resources of ordinary chondrite parent bodies. Mining Science 25 71-83

[13] Blutstein K, Przylibski T, Łuszczek K 2018 Zawartość mineralów FeNi w chondrytach H jako wskaźnik zasobności poziomierskich skal rudonośnych w wybrane metale (in Polish). Przegląd Geologiczny 66(12) 776-784

[14] Gaffey M, Bell J, Brown H, Burbine T, Piatek J, Reed K, Chaky D 1993 Mineralogical Variations within the S-Type Asteroid Class. Icarus 106(2) 573-602

[15] Burbine T, McCoy T, Meiborn A, Gladman B, Keil K 2002 Meteoritic Parent Bodies: Their Number and Identification W: Asteroids III, The University of Arizona Press, Tucson

[16] Agursa HF, Richardson DC, Davis AB, Fahnestock E, Hirabayashi M, Chabot NL, Cheng AF, Rivkin AS, Michel P 2020 A benchmarking and sensitivity study of the full two-body gravitational dynamics of the DART mission target, binary asteroid 65803 Didymos. Icarus 349

[17] Skulteti A, Kereszturi A, Szabo M, Kereszty Zs, Cipriani F 2020 Mid-infrared spectroscopic
investigation of meteorites and perspectives for thermal infrared observations at the binary asteroid Didymos. *Planetary and Space Science* **184**

[18] Michel P, Küppers M, Campo Bagatin A, Carry B, Charnoz S, de Leon J, Fitzsimmons A, Güttler C, Green SF, Hébrard E, Jutzi M, Karatekin O, Murdoch N, Pravec P, Sierks H, Snodgrass C, Tortora P, Tsiganis K, Ulamec S, Vincent JB, Wünnemann K, Carnelli I, Martino P, Barmouin OS, Chabot N, Cheng A, Rivkin A 2020 Science and Planetary Defense Aspects of the ESA Hera Mission, 51st Lunar and Planetary Science Conference, held 16-20 March, 2020 at The Woodlands, Texas. LPI Contribution No. 2326

[19] Bowles NE, Snodgrass C, Gibbings A, Sanchez JP, Arnold JA, Eccleston P, Andert T, Probst A, Naletto G, Vandaele AC, de Leon J, Nathues A, Thomas IR, Thomas N, Jorda L, Da Deppo V, Haack H, Green SF, Carry B, Donaldson Hanna KL, Leif Jorgensen J, Kereszturi A, DeMeo FE, Patel MR, Davies JK, Clarke F, Kinch K, Guilbert-Lepoutre A, Agarwal J, Rivkin AS, Pravec P, Fornasier S, Granvik M, Jones RH, Murdoch N, Joy KH, Pascale E, Tecza M, Barnes JM, Licandro J, Greenhagen BT, Calcutt SB, Marriner CM, Warren T, Tosh I 2018 CASTAway: An asteroid main belt tour and survey. *Advances in Space Research* **62**(8) 1998-2025

[20] Yuichi T, Makoto Y, Masanao A, Hiroyuki M, Satoru N 2013 System design of the Hayabusa 2 – Asteroid sample return mission to 1999 JU3. *Acta Astronautica* **91** 356-362

[21] McSween H, Huss G 2010 Cosmochemistry, Cambridge University Press, Cambridge

[22] Baer J, Chesley S, Matson R 2011 Astrometric masses of 26 asteroids and observations on asteroid porosity. *The Astronomical Journal* **131**(5) 1-12

[23] Gaffey M, Gilbert S 1998 Asteroid 6 Hebe: The probable parent body of the H-type ordinary chondrites and the IIE iron meteorites. *Meteoritics & Planetary Science* **33** 1281-1295

[24] Goldschmidt V 1937 The principles of distribution of chemical elements in minerals and rocks. *Journal of Chemical Society* 655-673

[25] Krzesińska A 2017 Contribution of early impact events to metal-silicate separation, thermal annealing, and volatile redistribution: Evidence in the Pułtusk H chondrite. *Meteoritics & Planetary Science* **52**(11), https://doi.org/10.1111/maps.12933

[26] Łuszczek K, Krzesińska A 2020 Copper in ordinary chondrites: Proxies for resource potential of asteroids and constraints for minimum-invasive and economically efficient exploitation. *Planetary and Space Science* https://doi.org/10.1016/j.pss.2020.105092

[27] Wedepohl K 1995 The composition of the continental crust. *Geochimica et Cosmochimica Acta* **59**(7) 1217-1232

[28] Dunn T, Burbine T, Bottke W, Clark J 2013 Mineralogies and source regions of Near-Earth asteroids. *Icarus* **222** 273-282