BULK CARBON AND SULFUR ABUNDANCES IN CARBONACEOUS METEORITES.

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Introduction: Cosmic dust and carbonaceous chondrites are of importance as major extraterrestrial source of carbon and organics, which possibly served as prebiotic seeds of life on the early Earth. One of science objectives of DESTINY+ is to characterize cosmic dust on the basis of physical and chemical properties directly measured prior to the atmospheric entry [1]. DESTINY+ is currently planned to be launched in 2024 and flyby Geminids-parent asteroid (3200) Phaethon in January, 2028 [1]. After the spacecraft is injected into a highly elliptical orbit around the Earth, it will gradually raise its orbit for about 2 years, to reach the Moon. Subsequently, it escapes from the Earth's gravity sphere through multiple lunar gravity assists, heading to Phaethon. Dust Analyzer (DDA) onboard DESTINY+ will directly measure cosmic dust during the entire mission phases, including the Earth's spiral orbit, lunar swing-by, interplanetary cruise, the Geminids dust stream and flyby of Phaethon [1].

DDA is an impact ionization time-of-flight mass spectrometer with integrated trajectory sensor, which will analyse micrometer and sub-micrometer-sized dust particles. The instrument will measure the particle chemical composition (mass resolution $m/\Delta m \approx$ 100-150), mass, electrical charge, impact velocity (about 10% accuracy), and impact direction (about 10° accuracy) [2]. Combined bulk chemistry and physical properties for measured dust particles are used to constrain the nature and origin of each dust particle. Carbon is a key element in DDA science, since it is directly linked with the mission objective.

Carbon (C) and sulfur (S) abundances of meteorites are key elements to reflect secondary thermal and aqueous history and/or redox state of their parent bodies. Previous studies indicate that total abundances of carbon and sulfur varies substantially among multiple classes of carbonaceous chondrites and carbonaceous achondrite (ureilite) [3,4] A comprehensive study of bulk C and nitrogen (N) for multiple petrologic classes of carbonaceous chondrites conducted using a single analytical method shows that the elemental abundances broadly correlate with the degree of secondary thermal and aqueous alteration over the petrologic types [5]. The study also indicate that no systematic differences are present between meteorite falls and finds, implying that terrestrial alteration has a minor effect on bulk C and N abundances [5].

Motivation of this study is to demonstrate bulk-meteorite C and S abundance measurement with a different analytical method from previous studies, using an advanced C and S analyzer. Once the feasibility of measurement is confirmed, variations in C and S abundances among petrologic types of meteorites are discussed and compared with those from previous studies.

Samples & Methods: Bulk C and S abundances were measured for total six meteorite samples, including different petrologic types of carbonaceous chondrites, Murchison (CM2), Allende (CV3), NWA 2086 (CV3) [6], NWA 5515 (CK4) [7], with two carbonaceous chondrites-related achondrites, NWA 6704 (CR chondrite-related achondrite) [8-11], and Almahata Sitta (coarse-grained ureilite) [7, 12]. Almahata Sitta is a recorded fall and other five are finds. Considered the caution that variations in carbon abundances in multiple types of carbonaceous chondrites tend to be affected by intra-meteorite heterogeneities [5], the mass of a few hundred mg was used for measurement of each sample.

C and S analyses were performed using Elementar inductar CS cube carbon and sulfur analyzer at Institute for Geo-Cosmology, Chiba Institute of Technology. The samples were pulverized using an agate mortar and pestle. The ceramic crucible was heated at 1100°C for 40 minutes using a muffle furnace to remove the adsorbed contaminants. Meteorite samples of 175–389 mg (Table 1) weighed and placed in the ceramic crucible, and about 2 g of tungsten/tin mixture and 0.5 g of pure iron were added as combustion improver. During the analysis, high-purity G1 grade oxygen (>99.99995%) was supplied at a rate of 450 mL/min to create a pure oxygen atmosphere, and the sample was introduced into a solid-state induction furnace where a voltage of 2000 W was applied to burn the sample. The carbon and sulfur in the sample were extracted as CO (partially CO_2) and SO_2, respectively. SO_2 was detected by the first non-dispersive infrared (NDIR) detector. In an oxidation tube (platinum silica-gel, 550°C), CO and SO_2 oxidized to CO_2 and SO_3, respectively. SO_3 was collected in a trap (cellulose), and CO_2 was detected with the second NDIR detector. The carbon and sulfur content of the sample was calculated from the detected concentrations of CO_2 and SO_2 using the calibration coefficients for steel, which are set in the instrument, since the calibration coefficients for C chondrites are not known.

Results and Discussion:

Feasibility of bulk C & S analyses. Bulk C and S abundances for the six meteorites measured in this study are given in Table 1, and those for carbonaceous meteorites in the previous studies [5, 7] are listed in Table 2. Elemental abundances of both C and S in this study are broadly similar to those of previous studies for the same petrologic types with an exception of S abundance of CK4 chondrites. While C abundance of Murchison in this study (2.043 wt%) is slightly lower than that from the previous study (2.70 wt%) [7], C abundance of Allende in this study (0.501 wt%) is higher than that in the previous study (0.27 wt%) [7]. S abundance of Murchison in this study (2.4266 wt%) is slightly lower than those of CM2 chondrites both from Antarctic and non-Antarctic meteorites in previous study (2.80 – 5.44 wt %) [5]. Note that S abundance of NWA 5515 CK4 chondrite (0.0545 wt %) in this study is significantly lower than those of CK4 chondrites both from Antarctic and non-Antarctic meteorites in the previous study (1.31 – 2.14 wt %). Except the S abundance in CK4 chondrite, the bulk-rock abundances for both C and S in this study comparable to those in previous studies indicate that analyses with the inductor C and S analyzer is feasible and valid.

Variation among petrologic types. Amongst carbonaceous chondrites measured, the CM2 chondrite displays the highest abundances, the CK4 chondrite shows the lowest and the CV3 falls in between both for C and S (Table 1). The bulk C and S abundances decrease with increasing thermal metamorphism, which is in line with previous studies [5]. For achondrites, CR-related achondrite NWA 6704 shows by far the lowest abundance both in C and S. The Almahata Sitta ureilite sample has the highest C abundance among all the samples measured with the S abundance comparable to that of CV3 NWA 2086. Further discussion on bulk C and S variations over petrologic types and on comparison with previous studies is pending analyses of additional samples by the analytical method used in this study.

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Table 1. Bulk C and S abundances of meteorites in this study.

Sample	Type	Weight [mg]	C [wt%]	S [wt%]
Murchison	CM2	275.6	2.043	2.4266
Allende	CV3	365.6	0.501	0.6521
NWA 2086	CV3	245.2	0.368	0.2806
NWA 5515	CK4	389.1	0.325	0.0545
NWA 6704	CR achondrite	376.4	0.010	0.006
Almahata Sitta	Ureilite	175.0	4.896	0.2354

Table 2. Bulk C and S abundances of meteorites in previous studies [5, 7]. Data from [5] are colored in gray.

Sample	Type	C [wt%]	S [wt%]
Antarctic	CM2	1.324 (ALHA 77306), 1.514 (Y-74662)	3.490 (Y-74662), 3.863 (ALHA 77306)
non-Antarctic, Falls	CM2	2.16 (Nogoya) - 4.05 (Mighei)	2.80 - 5.44
		2.70 (Murchison)	not available
non-Antarctic, Finds	CM2	2.62 (Kivesvaara)	not available
non-Antarctic, Falls	CV3	0.27 (Allende) - 1.50 (Grosnaja)	not available
non-Antarctic, Finds	CV3	1.14 (Leoville)	not available
Antarctic	CK4	0.061 (Y-693)	1.604 (Y-693)
non-Antarctic, Falls	CK4	0.07 (Karoonda)	1.31 - 2.14
non-Antarctic, Finds	CK4	0.28 (Maralinga)	not available
Antarctic	Ureilite	3.022 (Y-74659)	0.518 (Y-74659)
non-Antarctic	Ureilite	2.07 - 4.10	0.179 - 0.58