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Concepts of the Small Body Sample Return Missions - the 1st 10 Million Year Evolution of the Solar System

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Abstract Each type of asteroids and comets are important, serving as the unique puzzle pieces of the solar system. The countless number of small bodies spread vastly from the near-Earth orbits to the main belt and beyond Jupiter. Thus, in order to complete the whole puzzle, and hence requires a well-designed roadmap of sample return (SR) missions and international coordination. The main consideration is the accreting locations of various types of asteroids, which may be referred through their redox status and abundances of water and volatile components. C-complex asteroids are water and volatile-rich, likely accreted in the outer solar system. Two C-complex asteroids are being explored by Hayabusa-2 and OSIRIS-REx missions, respectively. In contrast, enstatite chondrite-like asteroids formed under extremely reducing conditions in the inner solar system. The samples returned from enstatite chondrite-like asteroids will clarify the nebular processes in the zone closest to the

Role of Sample Return in Addressing Major Questions in Planetary Sciences
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Sun, and reveal fractionation of the solar nebula along the radial direction, via comparing with those of the C-complex asteroids. The exploration will also shed light on the bulk compositions of the Earth and terrestrial planets accreted in the same region of the inner solar system.

The SR missions will focus on the first 10 Ma history of the solar system, including the initial condition, the nebular processes, and the accretion of planetesimals. Because the secondary processes that took place in planetesimals, such as thermal metamorphism, aqueous alteration, melting and differentiation, could largely erase the records of the nebular events, it is critically important to choose the primordial asteroid targets. Although C-complex asteroids accreted at low temperature in the outer solar nebula, they, especially those hydrated, could have suffered severe aqueous alteration as observed in CM chondrites. Other preferred targets are L-type asteroids, which probably contain abundant Ca-, Al-rich inclusions, the first solid assemblages of the solar system. Based on the roadmap of SR missions, we propose to return samples first from enstatite chondrite-like or L-type Near-Earth asteroids.

Keywords Solar system evolution · Protoplanetary disk · Asteroids · Comets · Sample return missions

1 Introduction

Small celestial bodies, namely asteroids and comets, are the remained planetesimals and/or their broken debris accreted in the protoplanetary disk. They have recorded the formation and early history of the solar system. In addition, the small bodies are referred to as the ‘building blocks” of the Earth and terrestrial planets; hence they are the key to probe the bulk compositions of the latter. Asteroids are classified into various spectral types (Bus and Binzel 2002; Demeo et al. 2009; Vernazza and Beck 2016), suggestive of different compositions and therefore their formation locations in the protoplanetary disk. Each type of asteroids and comets need to be explored and sampled, in order to draw the whole picture of the solar system evolution. Up to date, a number of asteroids and comets have been explored or selected as the targets of future missions by NASA, ESA, and JAXA. However, only one small body mission was so far planned by the China National Space Administration (CNSA), which will return samples from the asteroid 2016 HO3, a quasi-satellite of the Earth, followed by remote sensing of the comet 133P in the main belt. One of the reasons is that CNSA has already planned many other missions before 2035, including the phase 4 of Chang’E program (consisting of 3 landing missions at the lunar south pole), two Mars missions (the 1st one consisting of an orbiter, a lander and rover, and the 2nd one returning samples), and one mission to Jupiter and its satellites.

In order to have more contributions to exploring of the origin and early evolution of the solar system, we need to plan and carry out additional SR missions of asteroids and comets. This is possible, because the cost of small body SR missions can be reduced to a low level within the budget of the Strategic Priority Program on Space Science of the Chinese Academy of Sciences (CAS). For this purpose, the in advance study project of “sample return missions of small bodies” was selected and supported by CAS. The goals of this in advance study are to clarify the key scientific questions addressed by small body sample return missions, outline the exploration roadmap, and demonstrate the key techniques including self-navigation, sampling and sample capsule. The additional small body SR missions will be complementary to the deep space exploration program of CNSA, and should be coordinated with ongoing and future missions via international cooperation.

What is the strategy of the small body SR missions? There are more than one million of asteroids observed plus a large number of comets. The reflectance spectra of asteroids were classified into about 26 types (Bus and Binzel 2002; Demeo et al. 2009). The representative asteroids of the major types have been explored or chosen as the candidate targets for future missions, e.g. Vesta (V-type) by Dawn mission (Coradini et al. 2011), Psyche (M-type, metallic) by Psyche mission, Itokawa (S-type) by Hayabusa mission (Abe et al. 2006), Ryugu (C-type) by Hayabusa-2 (Kitazato et al. 2019), and Bennu (B-type) by OSIRIS-REx (Lauretta et al. 2019). On the other hand, the asteroid targets were also selected based on their orbits, e.g. Eros and Mathilde (Near Earth asteroids, NEA) by NEAR mission (Veverka et al. 2000), Vesta and Ceres (main belt asteroids) by Dawn mission, and Trojan asteroids of Jupiter by Lucy mission. The asteroid 2016 HO_3 (the quasi-satellite of the Earth) will be explored and sampled by China SR mission; whereas Phobos and Deimos (the satellites of Mars) are the targets of MMX mission of JAXA (Galimov 2010). Different from previous missions, we made a proposal of a serial SR missions based on the key questions of the origin and early evolution of the solar system. Furthermore, the proposed SR missions will combine with other ongoing and planned missions, in order to depict the early history of the solar system. After drawing up the potential roadmap of small body exploration, we propose to explore and return samples first from enstatite chondrite-like asteroids, which accreted under extremely reducing conditions in the inner solar system likely closest to the Sun.

2 Key Questions of the 1st 10 Ma Evolution of the Solar System

Asteroids and comets are the "fossil" of the solar system, preserving records of the initial condition and various processes of the solar nebula, accretion of planetesimals, and various secondary events that took place in asteroids (including thermal metamorphism, aqueous alteration, melting and differentiation). In addition, they were the building blocks of the Earth and terrestrial planets. In order to achieve the main scientific goals of SR missions, the key questions are focused on the 1st 10 Ma evolution of the solar system; whereas the secondary processes took place in the planetesimals after accretion will not be discussed in this work.

According to the formation hypothesis of the solar system and the astronomic observations of extrasolar systems, the solar system originated from a piece of collapsed molecular cloud, and the nebular disk evolved into the highly heterogeneous planetary system (Boss and Keiser 2015; Ciesla and Charnley 2006). The 1st 10 Ma evolution and fractionation of the protoplanetary disk largely determined the bulk compositions of the Earth and other terrestrial planets, hence their diverse physical properties. The main episodes of the 1st 10 Ma history can be divided into: (1) The initial solar nebula before condensation of the first solid assemblages (i.e. Ca-, Al-rich inclusions, CAIs hereafter); (2) Various nebular processes, including gas-solid condensation, heating events, solid-gas reactions (alteration), and transportation of gas and solid assemblages; (3) Accretion of planetesimals, to be followed by migration effects of planets. These main episodes are discussed in detail in the following subsections.

2.1 Initial Condition of the Protoplanetary Disk

The original solar nebula was composed of dust and gaseous molecules. A key question is about the dust/gas initial ratio. The nebular gas is expected homogeneous in chemical and isotopic compositions, whereas the dust particles should have preserved their distinct isotopic compositions of various stellar sources. The pre-existing dust particles are therefore referred to as the presolar grains, which have been found in the fine-grained matrix of primordial chondrites, based on their large isotopic anomalies (Nittler and Ciesla 2016; Zinner 1998). Except for the fine-grained matrix, other components in primitive chondrites including CAIs, silicate chondrules and metal-sulfide assemblages have experienced various high temperature processes in the nebula, which should have destroyed any pre-existing presolar grains. The abundances of presolar grains in chondrites were therefore reported as the fine-grained matrix-normalized values, and the maximum values are ∼1000 ppm for presolar diamond (Lewis et al. 1987; Zinner 1998), up to ∼200 ppm for presolar SiC (Floss and Stadermann 2009; Zhao et al. 2013) and 125-220 ppm for presolar silicates (Floss and Haenecour 2016; Floss and Stadermann 2009; Haenecour et al. 2018; Nittler et al. 2018). Higher abundances of presolar silicates up to an average of ∼500 ppm (with a maximum of 1.5%) were reported in primitive interstellar dust particles (IDPs) (Busemann et al. 2009; Floss and Haenecour 2016). However, all the reported abundances of presolar grains are rather low, especially the abundances of presolar silicates in primitive chondrites are at least a factor of 2 orders too low (Hoppe et al. 2017). The very low abundances of presolar grains indicate a very low dust/gas ratio of the initial solar nebula, although it cannot be excluded that the presolar dust grains were highly dominated by a single stellar reservoir. In this scenario, the predominant presolar grains from this stellar reservoir should have the same solar isotopic compositions, hence they were not identified as presolar origins by in situ isotope measurement. Alternatively, most of the solid materials of the planetary disk re-condensed from the homogenized nebular gas, which could have been produced by evaporation of the pre-existing dust via heating events or in the hot zone closest to the Sun.

Another key question is the spatial distribution of presolar grains in the initial solar nebula, homogeneous or heterogeneous? Most studies of presolar grains were focused on carbonaceous chondrites, with a few on non-carbonaceous chondrites. Isotope mapping of the acid-residue from Qingzhen EH3 chondrite revealed the abundance ratios of various presolar grains (e.g. ∼1/400 of X SiC grains/mainstream SiC, 1/4 of X-Si_3N_4/X-SiC) (Lin et al. 2002) different from those of Murchison CM2 carbonaceous chondrite (∼1% X SiC grains relative to Mainstream, 1/30 of X-Si_3N_4/X-SiC) (Zinner 1998). The relatively lower abundance of X-grains in Qingzhen EH3 chondrite was confirmed by the ion mapping of SiC from Sahara 97166 (EH3), which resulted in 0.36% X SiC relative to Mainstream SiC (Besmehn et al. 2001). Another hint for heterogeneous distribution of presolar grains was the isotopic anomalies of Cr, Ti, Ni and O between carbonaceous chondrites and non-carbonaceous ones (Trinquier et al. 2009; Warren 2011b). The identification of nanoparticles of Cr-oxides with δ^{54}Cr of $> 1500‰$ supplied with convincing evidence that the ^{54}Cr-enrichment was due to the addition of supernova ejecta (Qin et al. 2011). Is it possible that the initial solar nebula was homogeneous but was later mixed with the supernova ejecta?

Another key question is the temperature and its spatial and temporal variation in the solar nebula. After the formation of the Sun, a temperature gradient in the protoplanetary disk could be expected because of the sunlight and the strong irradiation from the T-Tauri proto-Sun (Shu et al. 1996). The presence of presolar SiC and/or oxides in the primordial enstatite chondrites (Lin et al. 2002), ordinary chondrites (Choi et al. 1998; Nittler et al. 1994) and carbonaceous chondrites (Tang and Anders 1988) suggests that the temperature in the accreting regions of these parent asteroids was low (<300-400 °C), in order to preserve the submicron-sized dust grains. This is consistent with the presence of presolar grains exclusively in primitive chondrites with petrographic type ≤3. The matrix-normalized abundance of presolar SiC (based on noble gas isotopes) seems quite similar among these chemical groups, 21.9 ppm for Qingzhen (EH3), 20.1 ppm for Semarkona (LL3.0) and 28.5 ppm for Orgueil (CI), but dropped immediately in thermal metamorphosed meteorites (Huss and Lewis 1995). The similar abundances of presolar SiC from the extremely reduced EH group (likely closest to the Sun) to the oxidized C-groups (far from the Sun) suggests that the wide nebular regions from the inner to the outer solar system have never been heated high enough to destroy the submicron-sized presolar SiC. However, the low temperature requirement for preserving the submicron-sized presolar grains seems to be in conflict with the high temperature gas-solid condensation at least in the enstatite chondrite-forming regions.

2.2 Condensation Under Various Redox Conditions

Regardless of the initial low temperature of the molecular cloud and the presence of presolar grains that require a maximum temperature of <300-400 °C as discussed above, fine-grained CAIs are high-temperature condensate assemblages of various refractory oxides and silicates found commonly in carbonaceous chondrites (e.g., Krot 2019; MacPherson and Grossman 1984). The coexistence and formation sequence of these refractory minerals of the fine-grained CAIs are well consistent with condensation from the gas with CI composition (Grossman 1972, 2010; Yoneda and Grossman 1995). Furthermore, the mineral assemblages and bulk compositions of the fine-grained CAIs vary from corundum-bearing ultra-refractory, to spinel-melilite-rich, and to spinel-pyroxene-rich, along the condensation trajectory from high to low temperatures (Lin and Kimura 2003). Amoeboid olivine assemblages (AOAs) can be referred to as gas-solid condensation at lower temperatures than typical CAIs, with spinel-/anorthite-bearing AOAs filling the gap between CAIs and AOAs (Aléon et al. 2002; Komatsu et al. 2001; Krot et al. 2004). The presence of fine-grained CAIs suggests gas-solid condensation in the solar nebula. However, it is unknown where the condensation process took place. One possibility is that fine-grained CAIs condensed in the region closest to the Sun. This is supported by the typical ^{16}O-enriched oxygen isotopic compositions of CAIs (Clayton et al. 1973), which has been identified as the composition of the Sun (Hashizume and Chaussidon 2005; McKeegan et al. 2011). Recent oxygen isotope mapping of primitive chondrites found unusually ^{16}O-enriched CAIs with δ^{17}O and δ^{18}O of $-77‰$ and $-75‰$, respectively (Sakamoto and Kawasaki 2019), probably formed closest to the Sun and hence recorded its undiluted oxygen isotopic composition.

Another key question of the solar nebular condensation was raised by the formation of enstatite chondrites. These meteorites are characteristic of unique opaque mineral assemblages, consisting of various sulfides of typical lithophile elements (e.g. oldhamite, niningerite, alabandite, djerfisherite, sphalerite, daubréelite), perryite, schreibersite and Si-rich Fe-Ni metal (El Goresy et al. 1988; Keil 1989; Lin and El Goresy 2002). In addition, the silicates are predominant FeO-poor enstatite. All these minerals and their compositions required extremely reducing conditions, which could be achieved by increasing the C/O ratio from the solar value (0.54) up to >0.8 (Grossman et al. 2008; Larimer and Bartholomay 1979), although the mechanism of enhancing C/O ratio of the solar nebula remained unknown. On the other hand, the high-temperature condensation of the predominant constituents of enstatite chondrites seems to be inconsistent with the preservation of presolar grains, because the latter requires a low temperature (<300-400 °C) as discussed above. This is different from the case of fine-grained CAIs, because they are minor objects of chondrites and could be carried from the region closest to the Sun and accreted together with presolar grains in chondrite-forming ones. In contrast, it is difficult to have a mechanism of transporting all these components (sulfides, Si-bearing metal and enstatite, with different densities and other properties) to the same region, where they accreted together with the pre-existing presolar grains. Alternatively, the constituent minerals condensed under extremely reducing conditions in the enstatite chondrite-accreting regions, and the presolar grains were added after the condensation from the outer region. In addition, other questions are the origin of the extremely reducing condition and the spatial and genetic relationship between the condensation regions of CAIs and enstatite chondrites.

Variation in redox along the solar disk was revealed by oxygen fugacity of various groups of chondrites and the redox of terrestrial planets. It becomes more reducing towards the Sun, as indicated by the decreasing of FeO contents of silicates and increasing of the metallic core/silicate mantle ratios in the sequence of Mars, Earth, Venus and Mercury. Meteorites show a wide range of redox, from highly reducing of enstatite chondrites to ordinary chondrites and then the oxidizing CV chondrites. Although the accreting regions of their parental asteroids are unknown, the oxygen fugacity was positively correlated with the abundances of water and volatile components. It is reasonable to assume that the protoplanetary nebula became more reducing towards the Sun. In addition, the oxygen fugacity profile should have been established before the condensation of the fine-grained CAIs and the constituent minerals of enstatite chondrites. Hence, the related key question is how the solar nebula evolved from homogeneous into heterogeneous before condensation?

2.3 Heating Events

Distinct from the condensation of fine-grained CAIs depicted above, there were at least two transient heating events in the protoplanetary disk. One of the heating events corresponds to the formation of coarse-grained CAIs. The coarse-grained CAIs share the similar mineral, chemical and isotopic compositions of the fine-grained ones, except for their igneous textures. It was generally accepted that the coarse-grained CAIs crystallized from Ca-, Al-rich melts. However, the heating mechanism and the precursors of these refractory inclusions are controversial. A common hypothesis is the X-wind model (Shu et al. 1996), which suggests CAIs as relict refractory materials by evaporating loss (up to 90%) of Mg and Si from CI-like precursor at a distance about 0.06 AU to the Sun. Many observations of coarse-grained CAIs can be explained by the X-wind model, e.g. the igneous textures, heavier isotope enrichment of Mg and Si, fast cooling, and identical features of CAIs from different groups of chondrites. However, the X-wind model has also been critically examined, and a number of internal inconsistencies were reported (Desch et al. 2010). In addition, the overlapping of bulk compositions between the fine-grained CAIs and the coarse-grained ones (compact type A and B) along the condensation trajectory suggests that the latter can be produced by melting of the former without a significant evaporating loss (Lin and Kimura 2003). As discussed above, the fine-grained CAIs show convincing evidence for gas-solid condensation, instead of being heated and melted by a transient event. Another discovery is the genetic relationship between type C CAIs and the fine-grained anorthite-spinel-rich inclusions (ASIs). The typical Type A CAIs reacted with the nebular gaseous SiO_2, producing the ASIs; and the latter was finally heated and melted to crystallize Type C CAIs (Lin and Kimura 1998). It was also noticed that a few of type B CAIs had experienced multiple heating events, as indicated by their high Na abundances and the correlation with the åkermanite contents of melilite (Lin and Kimura 2000; MacPherson and Davis 1993). Based on the mineralogy, petrography, oxygen isotope compositions, and trace element abundances, the igneous CAIs formed by incomplete melting of refractory precursors in an ^{16}O-rich gas likely near the protosun (Krot et al. 2018).

The other heating event was related to the formation of chondrules. This heating event was probably later by about 1-3 Ma than the formation of typical CAIs based on Al-Mg and U-Pb radiometric dating (Amelin et al. 2002; Bouvier and Wadhwa 2010; Kita et al.

2005). There are some chondrules, especially Al-rich chondrules, with the initial $^{26}Al/^{27}Al$ ratios plotted between CAIs and chondrules (Bizzarro et al. 2004), they could be due the presence of mini-CAIs or the debris of CAIs captured by the chondrules (Krot et al. 2006). Most chondrules formed via incomplete melting of isotopically diverse solid precursors, including CAIs, AOAs, fragments of pre-existing chondrules, and fine-grained matrix, by local transient heating events in ^{16}O-poor regions (Krot et al. 2018). In addition, the heating events of chondrules are distinct from that of the igneous CAIs, since they show different cooling rates with 10 $\sim$ 1000 °C/hr for chondrules (Lofgren 1996) whereas $<$ 5 °C/hr for the igneous CAIs (Stolper and Paque 1986). A much higher cooling rate up to 10^5-10^6 K/hr was reported in a phenocryst in a CO chondrite type-II chondrule (Yurimoto and Wasson 2002). The possible mechanisms are the X-wind model (Shu et al. 2001, 1996), lightning heating and shock heating (Connolly et al. 2006). The FeO contents of olivine and pyroxene in chondrules are related with the redox condition of their host chondrites, favoring for local heating of chondrules. This is also distinct from the common reservoir of CAIs from various groups of chondrites discussed in the next subsection.

2.4 Transportation and Fractionation of the Protoplanetary Disk

Fractionation of the protoplanetary disk, from initially homogeneous to highly heterogeneous, requires transportation of materials along the radial direction of the disk. The coexistence of CAIs with presolar grains argues for their different origins and delivering from distinct locations as discussed above. It was noticed that most CAIs from various groups of chondrites share the same petrographic features, mineral chemistry, oxygen isotopic compositions and the initial $^{26}Al/^{27}Al$ ratios (Guan et al. 2000; Lin et al. 2003; McKeegan et al. 1998), suggestive of the same reservoir. The differences of CAIs between the host chondrites are likely secondary, which could be attributed to alteration reactions in the accretion regions and/or the parent bodies of chondrites. This discovery further supports that CAIs in chondrites were not local products but delivered from other regions. According to the X-wind model, all CAIs were produced in the region very close to the proto-Sun, and then ejected to the whole protoplanetary disk (Shu et al. 1996). The discovery of CAIs in comet wild 2 sampled by Stardust mission supplies with robust evidence for the long distance transportation of CAIs (McKeegan et al. 2006; Zolensky et al. 2006). In addition, the recently reported highly C-rich clast ($\sim$100 µm) in CR2 LaPaz Icefield 02342 is probably a cometary microxenolith (Nittler et al. 2019). This discovery supports the idea of a radially inward transportation of materials from the outer protoplanetary disk into the CR reservoir. Another convincing evidence for the transportation in the nebular disk is the presence of dust-like pyroxene clasts in primitive enstatite chondrites, e.g. Qingzhen (EH3) and Yamato 691 (EH3) (Lin and El Goresy 2002; Rambaldi et al. 1983). The dust-like particles are Ni-poor micron-sized Fe metal, reduced from FeO of the silicates. The high FeO-contents of the silicate clasts suggest formation under oxidizing conditions, and then transported into the reducing regions of enstatite chondrites.

Before the condensation of the fine-grained CAIs and the constituent minerals of enstatite chondrites, the protoplanetary disk had already been evolved into heterogeneous. As discussed above, the fine-grained CAIs condensed from the nebula with the solar C/O ratio of $\sim$0.54, whereas the formation of enstatite chondrites required a much reducing condition with the C/O ratio $>$0.8. A simplified mechanism of enhancing the C/O ratio is fractionation between H, O and C via condensation and evaporation of water ice and organic materials across the snow line in the protoplanetary disk. The H_2O vapor and volatile organics could diffuse outwards, and re-condensed beyond the snow line; whereas the water ice and solid organics moved inwards due to the drag force of gas. This process would separate H_2O from the refractory organics, and consequently increasing the C/O ratio towards the Sun. On the other hand, water ice would concentrate close to the snow line, increasing the dust/gas ratio there and consequently feeding the formation of Jupiter. This scenario also explains the variation of redox among chondrites, and the correlation of redox with water and volatile abundances. It is expected that the isotopic anomalies of water ice (or preserved as oxides via reactions with metallic Fe-Ni and/or sulfides) and organics should be more significant in comets that accreted far from the snow line.

2.5 Accretion of Planetesimals and the Consequent Processes

CAIs, chondrules, opaque mineral assemblages, mineral fragments, presolar grains and the fine-grained matrix components all deposited together onto the midplane of the protoplanetary disk, forming pebble-sized chunks that grew into km-sized planetesimals probably by gravitational instability and turbulent collision (Chambers 2004). Little knowledge of the growing process of planetesimals was confirmed, since all meteorites are small in size and there were no representative samples of such large planetesimals. On the other hand, the explored asteroids are commonly composed of two parts (contact binary asteroids), which appears to be connected together via a collision of two smaller lobes. Simulations on the formation of planetesimals also showed that a part of the materials were contributed from other regions far away from the accreting site (Chambers 2004). Because of the isotopic heterogeneity of the protoplanetary disk, it is possible to track the distinct reservoirs of asteroids by precise isotope analysis of the samples collected from different sites of the targets.

After accretion, planetesimals usually experienced various degrees of secondary processes, such as thermal metamorphism, aqueous alteration, melting and differentiation. These processes are important, especially for the formation of planets. On the other hand, they would have largely erased the records of the nebular processes. C-complex asteroids are generally considered most primitive, and they are the preferred targets for exploration. However, some C-complex asteroids, especially those highly enriched in water, likely have suffered severely aqueous alteration. An example of aqueous alteration is CM2 chondrites. In Murchison and many other CM2 chondrites, most olivine grains in the fine-grained matrix and even in chondrules were heavily altered into phyllosilicates. Another indicator of aqueous alteration is the abundance of presolar silicates, which can be shown as the abundance ratio of presolar silicate/SiC. As mentioned above, presolar SiC grains are submicron-sized and very sensitive to temperature. Presolar silicates are also submicron-sized (0.2-0.5 μm predominantly), hence sensitive to temperature too. In addition, presolar silicates were readily erased by aqueous alteration even under low temperature. NanoSIMS mapping of presolar grains in the CM Sutter's Mill meteorite reported the presolar silicate/SiC abundance ratio of $<1/32$ (Zhao et al. 2014), much lower than those in CR and other less aqueous altered primitive chondrites (e.g. 33 in GRV 021710) (Zhao et al. 2013).

2.6 Relationship Between the Inner and Outer Solar System

A new classification schematic of meteorites and planetary materials was proposed as carbonaceous and non-carbonaceous groups, based on the bimodal isotopic anomalies of Cr, Ti, and O (Warren 2011a). This bimodality was confirmed by isotope analyses of more elements including Ni (Nanne et al. 2019), Ba (Bermingham et al. 2016), Mo (Budde et al. 2016), Ru and W (Worsham et al. 2019). The carrier of ^{54}Cr-anomaly was successfully separated and identified as nano-particles of Cr-oxides, which was likely ejected by the explosion of a nearby supernova (Qin et al. 2011). Carbonaceous meteorites accreted in the outer solar system, and show enrichment in ^{54}Cr, ^{50}Ti and ^{62}Ni, in comparison with non-carbonaceous materials (including ordinary chondrites, enstatite chondrites, achondrites, the Earth, the Moon, Mars, Vesta) representative of the inner solar system (Qin et al. 2011; Warren 2011a). These discoveries revealed heterogeneous isotopic compositions in the protoplanetary disk, and the spatial isolation between CC and non-CC materials before the accretion of planetesimals. The key questions are how and when this process took place? It is obviously important to explore and sample both the representative CC and non-CC asteroids, in order to address these questions.

2.7 Distribution and Evolution of Organic Matter in the Protoplanetary Disk

Organic materials are common in comets (Capaccioni et al. 2015; Cody et al. 2011; Goesmann et al. 2015; Sandford et al. 2006), IDPs (Busemann et al. 2009) and primitive chondrites (e.g., Alexander et al. 2017; Busemann et al. 2006; Cooper et al. 2001; Engel and Macko 1997; Nakamura-Messenger et al. 2006). They are widespread especially in the outer solar system. Organics in the protoplanetary disk constituted the source materials of the "building blocks" required by life, but their formation mechanisms and the subsequent modification processes are still poorly understood. The insoluble organic matter (IOM) usually shows large and highly heterogeneous D and ^{15}N-enrichments especially in the most primitive carbonaceous chondrites and IDPs (Busemann et al. 2006; Nakamura-Messenger et al. 2006), suggestive of the preservation of the primitive organics of the early solar system. However, the origins of the isotopic anomalies are unresolved, produced in the interstellar medium or the outer solar system (Alexander et al. 2017, 2008). In addition, organic materials can be readily modified by thermal and aqueous alteration reactions in the parent asteroids. The IOM in the Tagish Lake carbonaceous chondrite shows correlation with the parent body aqueous alteration, suggesting that at least some organic compounds formed in the parent asteroid (Herd et al. 2011). Other organic grains from CR chondrites showed association with carbonates and have more processed organic matter in the rims, providing evidence for highly aromatic and N-bearing organic synthesis by the parent body fluid (Vollmer et al. 2014). Hence, the samples returned from comets and the most primitive asteroids (such as D-type) that avoided the thermal and aqueous alteration reactions in the parent bodies are critically important to understand the formation and evolution of organic matter in the interstellar medium and the outer solar nebula.

Other key question is the distribution and modification of organic matter in the inner solar system. Compared with those accreted in the outer solar system, organic matter in ordinary chondrites and enstatite chondrites show distinct isotopic features. The organics in the thermally metamorphosed Abee enstatite chondrite is the most D-depleted of extraterrestrial samples (Remusat et al. 2012), whereas IOM in unequilibrated ordinary chondrites is extremely D-enriched and negatively related with the H/C ratios (Alexander et al. 2010; Remusat et al. 2016). Furthermore, organic carbon could play a key role in the redox state of the inner solar system, although ordinary chondrites and enstatite chondrites contain low organic matter and the majority of the organic materials of the Earth could be delivered from carbonaceous asteroids based on the H and N isotopes (Furi and Marty 2015; Marty et al. 2016). However, any possible genetic link between organics, amorphous and crystalline graphite in the nebula close to the Sun is unknown. The step heating of the Abee enstatite chondrite suggested that the graphite was not derived from a pure thermal solid-state graphitization of the organic matter (Remusat et al. 2012). In addition, the EL3 Almahata Sitta MS-17 and MS-177 fragments contain two petrographic settings of graphite with distinct and heterogeneous ^{13}C-depleted compositions (El Goresy et al. 2017), suggestive of complex formation of graphite. Samples returned from the primitive asteroids accreted close to the Sun is very important to understand the evolution of organic materials in the inner solar system.

3 Concepts of Small Body Sample Return Missions

Distinct from the exploration of planets and their satellites, samples returned from small bodies play the unique roles of understanding the formation and evolution of the solar system, especially during the first 10 Ma. The major key questions can only be addressed by analyzing the returned samples using the state-of-art facilities in laboratories, which requires extremely high spatial resolution and/or very high precision analysis of isotopes and trace elements. The unique advantages of SR missions are below: (1) New samples not yet in the meteorite collections; (2) Linking the spectral types of asteroids with the groups of meteorites; (3) Maximum elimination of terrestrial contamination, especially for water and organics; (4) With full contextual information of the parental asteroids and/or comets; (5) Multi-site sampling of the same planetesimals; (6) Intact surface regolith samples for study of space weathering on small bodies at various orbits.

The major scientific goals will be focused on the 1st 10 Ma history of the solar system and how it evolved into the highly heterogeneous planetary system, including the initial condition of the solar nebula, the major nebular processes, and accretion of planetesimals. In order to achieve these purposes efficiently, it is required to design a roadmap of SR missions based on the key questions. There are other two key considerations of the target selection: (1) primordial asteroids avoided possible thermal metamorphism and aqueous alteration after accretion; (2) various spectral types of asteroids and comets, representative of different accretion locations in the protoplanetary disk. It is critically important to return samples from the inner and outer solar system, respectively. The concepts of small body SR missions are illustrated in Fig. 1.

3.1 Scientific Goals of SR Missions

The scientific goals of SR missions are to address the key questions discussed above, mainly focused on the 1st 10 Ma history of the solar system. This period can be referred to as the birth of the solar system, and it has largely determined the formation and bulk compositions of the Earth and other terrestrial planets. Those secondary processes took place within planetesimals, such as thermal and aqueous metamorphism, melting and differentiation, could erase the nebular records and hence should be avoided in our project. The main scientific goals of small body SR missions include below:

(1) To understand the spatial distribution of presolar dust along the radial direction of the protoplanetary disk, the dust/gas ratio and its possible variation with time (or temperature gradient increasing towards the Sun). It is required to distinguish presolar grains from the solar condensates. These questions can be addressed via surveying of presolar grains in the returned samples from most primitive asteroids and comets, which accreted in various locations in the inner and outer solar system.
(2) To understand the nebular processes and their possible differences between the inner and outer systems. The key processes include high temperature gas-solid condensation, the heating events related to the formation of coarse-grained CAIs and chondrules, and

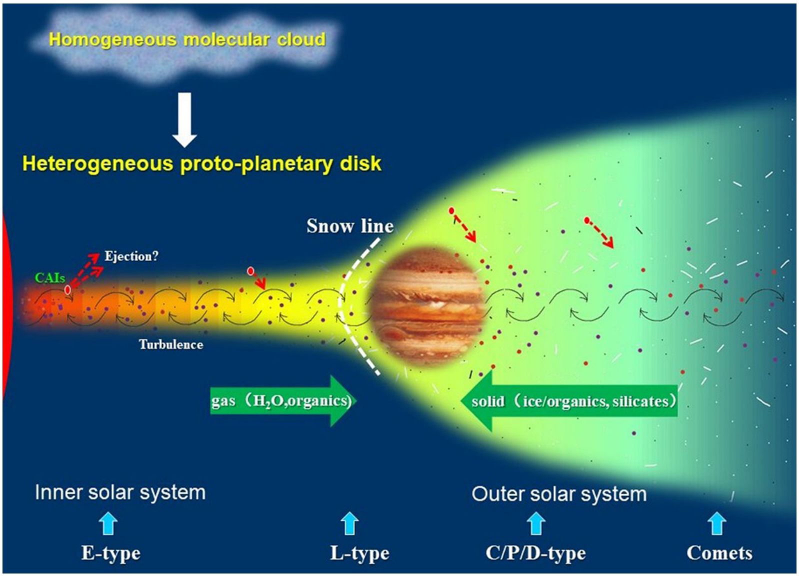

Fig. 1 Concepts of small body sample return missions

solid-gas reactions (alteration). It is required to clarify where and when these processes took place. Is there any genetic relationship between the condensation (cooling process) and the fast heating events?

(3) To understand the chemical fractionation of the protoplanetary disk in temporal and spatial dimensions. The fractionation in spatial dimensions requires samples returned from the representative asteroids and comets accreted in various locations, especially those from the inner and outer solar system, respectively. The key questions are the distributions of oxygen fugacity, water, organics and other volatile components along the radial direction of the protoplanetary disk. In addition, the fractionations were achieved by the transportation of materials, which probably started very early before the condensation of fine-grained CAIs and the unique opaque minerals of enstatite chondrites.

(4) To understand the isotopic anomalies and their correlation between CC and non-CC materials. Do the isotopic anomalies relate with the distribution of presolar dust or were they ejected from a nearby supernova? Besides the representative objects formed in the inner and outer solar system, respectively, candidate asteroids accreted close to or in the transition zone between them will shed light on the origin of the bimodality. A possibility is that the bimodality could be related to the fast formation of Jupiter, which placed a role of a barrier to stop the transportation of materials between the inner and outer solar system because of the strong gravity field of Jupiter.

(5) To understand the accretion of planetesimals, especially the possible reservoirs tracked by high precision isotope analysis. It could reveal how the different reservoirs were delivered to the same region and then accreted into the planetesimals.

(6) To establish the connection between the spectral types of asteroids with the chemical groups of chondrites or the returned samples if they are not in the collection of meteorites.

(7) To understand formation and evolution of organic compounds in the protoplanetary disk.

3.2 Target Selection

Primordial Asteroids After accretion, planetesimals likely experienced various degrees of thermal metamorphism and aqueous alteration. Thermal metamorphism is readily recognized, referred to as the petrographic types of chondrites. However, the effects of aqueous alteration were often overlooked, which could severely erase most nebular records even at low temperatures. In fact, water-rich C-complex asteroids were favorably selected as the targets. They are important to probe the distribution of water and organics in the protoplanetary disk, but may not a good choice in order to reveal the nebular processes. This has been demonstrated by the extensive aqueous alteration of CM2 chondrites, with most olivine and pyroxene (except the phenocrysts in chondrules) altered to serpentine-tochilinite intergrowths (Poorly Characterized Phases, PCP). Carbonates (calcite, dolomite) and magnetite are also common products of aqueous alteration, and their oxygen isotopes are ^{16}O-poor and show significant mass-dependent fractionation (e.g., Benedix et al. 2003; Jenniskens et al. 2012; Jilly-Rehak et al. 2018; Tyra et al. 2012). Another index of the aqueous alteration is the abundance ratios of presolar silicate/SiC and presolar silicate/oxide, since the submicron-sized presolar silicates are very sensitive to aqueous alteration, whereas both SiC and oxides are acid-resistant. Sutter's Mill CM chondrite shows severe aqueous alteration, and the ion mapping resulted in the presolar silicate/SiC abundance ratio of 2/55 (Zhao et al. 2014). The very low abundance of presolar silicates relative to SiC indicates that they have been destroyed by aqueous alteration. In contrast, GRV 021710 CR chondrite shows little aqueous alteration, with the presolar silicate/SiC and silicate/oxide ratios of 170/182 and 33/1 (Zhao et al. 2013), respectively. Hence, it is also important to select intact water-poor carbonaceous asteroids as targets, in order to avoid possible aqueous alteration. Dehydrated carbonaceous asteroids are also water-poor, but they have probably experienced aqueous alteration followed by degassing of thermal metamorphism.

Asteroids Formed in the Inner vs Those in the Outer Solar System In order to characterize the nebular processes at different locations in the protoplanetary disk, and to clarify the chemical fractionation of the solar system, it is essential to return samples from representative asteroids accreted at different locations, especially from both the inner and outer solar system. The formation locations of asteroids may be indicated by the oxygen fugacity and the abundances of water and volatile components. Enstatite chondrites are the most reduced meteorites, formed under a high C/O ratio ≥ 0.8. They can be referred to as the representative materials accreted closest to the Sun. On the other hand, carbonaceous chondrites are water-rich, and distinct from non-carbonaceous chondrites by the isotopic anomalies of O, Cr, Ti and other elements as depicted above. They accreted likely far from the Sun in the outer solar system. There are other types of asteroids dominantly in the outer main belt, including types D and P. Both D- and P-types are considered the most primitive among the asteroid population, probably formed far from the Sun. Their reflectance spectra are comparable to those of Hilda and Jupiter Trojans (DeMeo and Carry 2014; Grav et al. 2011; Vernazza and Beck 2016), respectively. D-type asteroids show a weak link with the Tagish Lake C2 ungrouped carbonaceous chondrite (Barucci et al. 2018; Fujiya et al. 2019; Hiroi et al. 2001), but the latter experienced severe aqueous alteration and contains abundant carbonates (Brown et al. 2000; Hiroi et al. 2001). Recently several small D-type asteroids (<600 m in diameter) were found by NEOShield-2 project, which are accessible to SR missions ($\Delta V < 7$ km/s) (Barucci et al. 2018). Other important types of asteroids are those not related to any meteorites. One of them is L-type, which probably contains the most abundant of CAIs. Spinel is a common mineral in CAIs and shows an absorption at about 2.4 μm, which are similar to the spectra of L-type asteroids (Sunshine et al. 2008).

Near Earth Asteroids The orbits of asteroids are readily modified by the gravity fields of planets, and the Near Earth asteroids likely immigrated from a wide range of spatial location. The spectral types of NEA and their distribution pattern are comparable to those of the asteroid belt (Binzel et al. 2019, 2004c; DeMeo and Carry 2014; Popescu et al. 2019). Hence, the Near Earth asteroids are the preferred targets for asteroid sample return missions. Other considerations are the suitable sizes, low rotation speeds, readily approachable orbits, and the launch windows.

Comets with Different Types of Orbits Comets are the most primitive small bodies, because they have been preserved at very low temperatures and never been melted. They suffered no aqueous alteration, hence preserved most records of the solar nebular processes and events. The orbits of comets can be classified as short period (Jupiter-family, Halley-type) and long period. It is possible that comets formed close to the snow line might have accreted more re-condensed water ice and organics from the vapor diffusing from the inner side of the snow line. In contrast, long period comets probably originated beyond the Kuiper belt, e.g. from the Oort cloud. The long period comets should have preserved the intact interstellar water ice and organics originated from various stellar sources. The samples returned from comets are especially important for understanding the distribution and evolution of organics, water and other highly volatile components in the solar system.

3.3 Heterogeneity and Multi-Site Sampling

According to numerical simulations of planetesimals and planets, the accretion at each zone has contributions from other zones of the protoplanetary disk, although the majority materials are local (Chambers 2004). In addition, the previous exploration of asteroids shows that the contact binary asteroids are common, e.g. asteroid 4179 Toutatis observed by the flyby of Chang'E-2 (Huang et al. 2013). Polymict breccia of chondrites were also reported. The Kaidun meteorite is composed of carbonaceous and enstatite chondrites, including various breccia of EH3-5, EL3, CV3, CR, CI-like, CM1-2 and R chondrites (MacPherson et al. 2009; Zolensky and Ivanov 2003). The Almahata Sitta meteorite consists mainly of ureilite with breccia of EH3, EL3, R and ordinary chondrites (Bischoff et al. 2010). Hence, it is required to obtain and return samples from different locations on the possibly heterogeneous surface of the target. High precision analyses of the isotopes and trace elements of the returned multi-site samples will shed light on the accretion process of planetesimals and transportation of materials in the protoplanetary disk.

3.4 Sampling and Curating Techniques

Besides common techniques of deep space exploration, e.g. energy, propulsion, communication, there are specific concerns on how to preserve the original status of the samples and to eliminate any possible contamination, which could happen during sampling, the return journey to the Earth, and curation in the laboratories. Special attention should be paid to organic materials, water, and other volatile components. In addition, new techniques of extremely low temperature from sampling process to the return journey, curation and analysis should be developed before returning samples from comets.

Sampling on a small body surface could be the most challenge technique and the most risky process of SR missions. Touch-and-go is still the preferable strategy in the first mission. Different from Hayabusa and OSIRIS-REx missions, full mechanical design of the sampling system will be applied, consisting of a robotic arm and a mechanical sampling device. The robotic arm supplies with a flexible touch with the surface regolith of the target, which can maintain the contact at least 3 seconds for sampling operation. Both main parts were connected with the self-adaptive joint, making sure well contact of the sampling device with the rough surface of the asteroid. This design has the advantage that the sampling device can be replaced for different tasks in future missions. Several sampling techniques, i.e. brushing, grabbing and electro-magnetic attracting (efficient only for chondritic samples, but erasing the magnetic information), are under consideration and test. The sampling system is designed to collect the surface regolith from three sites of the target, with the minimum mass of 2 g at each site. The materials used to manufacture the sampling device and the sample capsules will be carefully selected and verified, in order to eliminate possible contamination. The sample capsules will be vacuum-sealed and thermally isolated, with the temperature $< 80\ ^\circ\mathrm{C}$ when entering the atmosphere.

It will be a great challenge to return intact samples from comets. The key technique is how to preserve the comet samples under extremely low temperatures (e.g. $< -170\ ^\circ\mathrm{C}$) during the mission, including the sampling process, the long journey back to the Earth and re-entry of the atmosphere, and finally long-term curation, sample preparing and analysis. Besides water ice, comets also contain abundant high-volatile compounds, such as CH_4, CO, CO_2 and O_2 (Bieler et al. 2015; Capaccioni et al. 2015; Goesmann et al. 2015). In addition, contamination could be a severe issue, especially for organic materials. It is also critically important to keep the comet samples in their original status and forms, in order to preserve the micro-textures and heterogeneity in chemical and isotopic compositions, which recorded the various interstellar origins of these highly volatile components, the low-temperature processes of the solar nebula and formation of comets.

The lessons learnt from curation of Apollo lunar samples, comet dust samples, asteroid Itokawa samples, meteorites and IDPs can be used to design the small body return sample curation facilities. Besides preservation in ultra-pure N_2 atmosphere, a proportion of the asteroid samples could be kept in various conditions, e.g. high vacuum, liquid N_2, liquid He. Nondestructive analytical techniques, especially high resolution CT, can be applied to characterize and allocate the samples. However, new techniques should be developed in order to curate, prepare and analyze the comet samples. All of the procedures must be carried out under extremely low temperatures. In addition, the samples should be completely isolated from the lab atmosphere, in order to avoid possible contamination via condensation of the atmosphere components under such low temperatures.

3.5 Road Map of Sample Return Missions

In order to decode the first 10 Ma history of the solar system, a series of SR missions need to be planned and carried out in sequence. The targets should be primordial and their accretion zones cover the whole protoplanetary disk, from the inner to outer solar system in an order of enstatite chondrite-like asteroids (closest to the Sun), L-type (probably most CAIs-rich), C-, D- and P-types (outer solar system) and comets (most primitive objects).

The order of exploring of each type of the small bodies is scheduled mainly based on the approachability of the targets and the novelty of the samples. Because both asteroids Ryugu (C-type) and Bennu (B-type) originated likely in the outer solar system, hence the asteroids formed in the inner solar system closest to the Sun, i.e. enstatite chondrite-like asteroids, are selected as the top priority targets for the first SR mission of the space science program of CAS. In addition, L-type asteroids are also selected as the additional candidates.

The space technology will be developed accordingly, starting from those with higher Technology Readiness Level (TRL). SR missions of comets require special techniques of operating under extremely low temperatures in order to preserve the samples intact.

4 First Asteroid Sample Return Mission

4.1 Scientific Goals

According to the above discussion and the roadmap, the main scientific goals of the first asteroid SR mission of the space science program of CAS will aim to reveal the initial status and the consequent nebular processes under the extremely reducing condition in the inner solar disk. The discoveries will be compared with those by Hayabusa-2 and OSIRIS-REx missions, to clarify the chemical fractionation between the inner and outer solar system and understand how the solar system evolved into highly heterogeneous. In addition, the returned samples would shed light on the formation and the compositions of the Earth, Mercury and Venus accreted also in the inner solar system.

The specific questions to be addressed are: (1) The original status of the inner solar disk, including the abundance ratios of the dust (presolar grains)/gas and presolar silicate/SiC, and their differences from the outer solar system; (2) Inherent presence of water, organics and volatiles in the inner solar disk, and their fractionation along the radial direction towards the outer solar system; (3) Condensation under highly reducing conditions, and how the oxygen fugacity varied along the protoplanetary disk; (4) Possible heterogeneous accretion of planetesimals in the inner region, via orbit remote sensing and multi-site sampling of the target; (5) Space weathering and physical properties of the parental asteroids of enstatite chondrites; (6) Genetic relationship of the enstatite chondrite-like asteroids and enstatite chondrites, and their spatial distribution in the main melt; (7) Distribution of organic materials in the inner solar system, and their evolution revealed by comparison with those in the outer solar system.

4.2 Candidate Asteroids

According to the concepts and roadmap of small body SR missions, the high priority type of asteroids would be enstatite chondrite-like. The possible types include E, Xc, and Xe (Bus and Binzel 2002; Vernazza and Beck 2016). With consideration of accessibility, two NEA candidates have been tentatively selected, i.e. 1989 ML (10302) and 1982 DB (4660 Nereus). 1989 ML is about 248 m in diameter, with the rotation period of 19 hrs. It was classified as X-type or may be a shock-darkened ordinary chondrite (Binzel et al. 2001), or E-type (Mueller et al. 2007). 1989 ML was also chosen as a back-up target for MUSES-C (Fujiwara et al. 2000). A launch window is in July 2025, and the mission duration is about 4 years. 1982 DB is $500 \times 300 \times 240$ m in size, with the rotation period of 15 hrs (Brozovic et al. 2009). It was classified as Xe-type (Binzel et al. 2004a). The launch window is Feb. 2026, and the mission duration is about 5 years.

There is a large uncertainty whether or not 1989 ML and 1982 DB are really enstatite chondrite-like, because the spectra of enstatite chondrites measured in laboratory are almost featureless in terms of mafic silicate absorption bands. In addition, both 1989 ML and 1982 DB have high albedo, more close to enstatite achondrite (aubrite) than enstatite chondrite. Much more studies are required to compare the spectra of enstatite chondrites with the observations of candidate asteroids. Another helpful feature is that oldhamite shows high albedo at 0.56 μm (63%) and strong absorption band near 0.40 μm and weaker features at 0.546, 0.763, 1.151, and 1.831 μm (Izawa et al. 2013). Although oldhamite is a minor phase, it is the REE-rich Ca-sulfide and condensed rather early. The oldhamite-rich enstatite-chondrite-like asteroid would be very interesting.

L-type asteroids are rare, and not in the meteorite collections. They shows unique ∼2 micron absorptions attributed to FeO-bearing spinel, the most common constituent in CAIs. Based on the fitting of spectra, the abundance of CAIs in L-type asteroids could be up to 30 vol% (Sunshine et al. 2008; Tanga et al. 2015), as high by a factor of 3 as the most CAI-rich Allende CV3 chondrites. Two candidate asteroids of L-type, i.e. 2001 CC21 and 2012 DA14 (Binzel et al. 2004b; Takahashi et al. 2014), were selected. 2001 CC21 has a size of 0.6-1.3 km, with a rotation period of 5 hrs. The next launch window is June 2026. 2012 DA14 is much smaller, ∼30 m in diameter, with a rotation period of 9.5 hrs. The launch window is Feb. 2025.

4.3 Scouting of the Target Asteroid

In order to conduct the sampling safely on the surface of the target and to obtain the geological background, the global mapping of the asteroid will be carried out first. The essential information and key properties of the target include the Digital Elevation Model (DEM), distribution of boulders, mineral compositions and spatial distribution, presence and distribution of water and organics, thermal inertia and surface regolith, internal structure, magnetic field, the mass and density. Based on the density and composition of the surface materials revealed by spectral data, the porosity of the target can be well estimated. In addition, ground-penetrating radar can directly determine the inner structure of the asteroid. The interior structure of the target will be critical to distinguish a rubble-piled up object from the originally accreted one, and has constraints on its collisional evolution.

In order to reduce the budget of the SR mission, only the key scientific payloads will be considered. The tentatively configuration of the remote sensing instruments includes cameras, VNIS and thermal imaging system, radar sounder and receiver, magnetometer, and Rb atom clock and radio transmitter.

5 Concluding Remarks

Exploration of asteroids and comets plays the key role of understanding the origin and evolution of the solar system, and it is a long term task. Besides the CNSA SR mission aiming at the asteroid 2016 HO3, the quasi-satellite of the Earth, a series of small body sample return missions should be well designed and carried out at a lower cost. The main scientific goals will be focused on the first 10 Ma history of the solar system, including the initial condition of the solar nebula, the nebular processes and events, and the accretion of planetesimals. The exploration and study of the returned samples will reveal how the protoplanetary disk evolved into the highly heterogeneous solar system. To achieve these goals, primordial asteroids of various spectral types and comets, which accreted in different locations of the disk, should be explored and sampled. The accretion locations could be inferred from the redox status and the abundances of water, organics and other volatiles of the asteroids. The top priority targets are enstatite chondrite-like, because they formed under extremely reducing conditions likely closest to the Sun in the inner solar system. These asteroids are also the key to understand the formation and their bulk compositions of the Earth and terrestrial planets. They will shed light on the genetic relationship and fractionation between the inner and outer solar system, via comparing with those achieved by Hayabusa-2 and OSIRIS-REx missions both returning samples from the outer solar system. Another high priority targets are L-type asteroids, which probably contain the highest abundance of CAIs.

Two enstatite chondrite-like asteroids, 1989 ML and 1982 DB, and another two L-type asteroids, 2001 CC21, and 2012 DA14, have been tentatively selected as the candidate targets for the first SR mission of the space science program of CAS. All of them are Near Earth Asteroids, and approachable. The topography, mineral compositions, temperature distribution, density and internal structure of the target will be explored first, followed by touch-and-go sampling at two or three sites of the surface. The sampling system consists of a robotic arm and a collecting device that can be replaced with various designs, including brushing, grabbing and electro-magnetic attracting.

Because of the large number of the spectral types of asteroids and the long mission duration, the international coordination and collaboration could play a key role in the SR missions, ranging from scientific research, to selection and astronomical observation of the targets, and to the development of payloads.

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