

Igneous Rock Associations 24. Near-Earth Asteroid Resources: A Review

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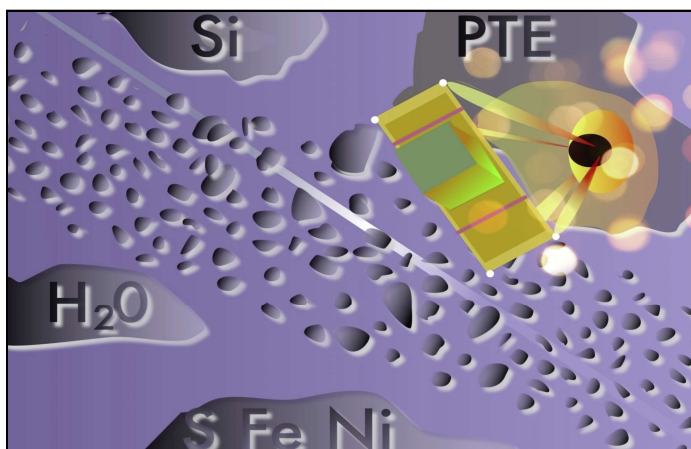
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Résumé de l'article

L'extraction de ressources naturelles situées au-delà de la Terre pour créer des produits peut être décrite comme une utilisation des ressources spatiales (URS). L'URS est actuellement examinée à la fois dans les secteurs public et privé. Les astéroïdes proches de la Terre (NEA) sont des cibles URS particulièrement prometteuses en raison de leur proximité relative et de leur enrichissement en deux ressources clés : l'eau et les éléments du groupe du platine (EGP). L'eau peut être utilisée pour créer des agents de propulsion pour vaisseaux spatiaux, ce qui en fait la seule ressource pour laquelle la demande est importante compte tenu de l'émergence du marché spatial actuel. Les EGP sont suffisamment précieux pour que leur importation sur le marché terrestre soit potentiellement économique, ce qui en fait l'autre ressource potentielle étant donné l'état embryonnaire actuel de l'URS. Bien qu'il soit possible de récupérer des matériaux sur un NEA, le faire à une échelle économique nécessitera des développements importants dans des domaines tels que la robotique autonome et la technologie de propulsion. Un paramétrage tenant compte de la taille des astéroïdes, de la concentration des ressources et de l'accessibilité conduit à seulement sept et trois cibles NEA parmi la population connue, potentiellement exploitables pour l'eau et les EGP, respectivement. Il est nécessaire de mettre davantage l'accent sur l'observation spectrale des astéroïdes afin de mieux documenter la sélection des cibles pour les premiers vaisseaux prospecteurs. L'absence de précédent juridique pour la vente de ressources extraterrestres est une complication supplémentaire. Le Traité sur l'espace interdit l'appropriation des corps célestes mais ne fait aucune référence explicite à leurs ressources, tandis que les États-Unis et le Luxembourg ont adopté une législation autorisant leurs citoyens à posséder et à vendre des ressources spatiales. Que ces lois fassent l'objet de clarification ou de contradiction est sujet à débat.

SERIES



Igneous Rock Associations 24. Near-Earth Asteroid Resources: A Review

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SUMMARY

The extraction of natural resources located beyond Earth to create products can be described as space resource utilization (SRU). SRU is under active investigation in both the public and private sectors. Near-Earth asteroids (NEAs) are particularly promising early SRU targets due to their relative proximity and enrichments in two key resources: water and platinum group elements (PGEs). Water can be used to create rocket propellant, making it the only resource with significant demand given the current nascent state of the space market. Platinum group elements are valuable enough that their import to the Earth market is potentially economical, making them the other prospective resource in the current embryonic state of SRU. While it is possible to retrieve material from a NEA, doing so on an economical scale will require significant developments in areas such as autonomous robotics and propulsion technology. A parameterization accounting for asteroid size, resource concentration, and accessibility yields just seven and three potentially viable NEA targets in the known population for water

and PGEs, respectively. A greater emphasis on spectral observation of asteroids is required to better inform target selection for early prospecting spacecraft. A further complication is the lack of a legal precedent for the sale of extraterrestrial resources. The Outer Space Treaty prohibits the appropriation of celestial bodies but makes no explicit reference to their resources while the U.S.A. and Luxembourg have passed legislation entitling their citizens to own and sell space resources. Whether these laws are a matter of clarification or contradiction is the matter of some debate.

RÉSUMÉ

L'extraction de ressources naturelles situées au-delà de la Terre pour créer des produits peut être décrite comme une utilisation des ressources spatiales (URS). L'URS est actuellement examinée à la fois dans les secteurs public et privé. Les astéroïdes proches de la Terre (NEA) sont des cibles URS particulièrement prometteuses en raison de leur proximité relative et de leur enrichissement en deux ressources clés : l'eau et les éléments du groupe du platine (EGP). L'eau peut être utilisée pour créer des agents de propulsion pour vaisseaux spatiaux, ce qui en fait la seule ressource pour laquelle la demande est importante compte tenu de l'émergence du marché spatial actuel. Les EGP sont suffisamment précieux pour que leur importation sur le marché terrestre soit potentiellement économique, ce qui en fait l'autre ressource potentielle étant donné l'état embryonnaire actuel de l'URS. Bien qu'il soit possible de récupérer des matériaux sur un NEA, le faire à une échelle économique nécessitera des développements importants dans des domaines tels que la robotique autonome et la technologie de propulsion. Un paramétrage tenant compte de la taille des astéroïdes, de la concentration des ressources et de l'accessibilité conduit à seulement sept et trois cibles NEA parmi la population connue, potentiellement exploitables pour l'eau et les EGP, respectivement. Il est nécessaire de mettre davantage l'accent sur l'observation spectrale des astéroïdes afin de mieux documenter la sélection des cibles pour les premiers vaisseaux prospecteurs. L'absence de précédent juridique pour la vente de ressources extraterrestres est une complication supplémentaire. Le Traité sur l'espace interdit l'appropriation des corps célestes mais ne fait aucune référence explicite à leurs ressources, tandis que les États-Unis et le Luxembourg ont adopté une législation autorisant leurs citoyens à posséder et à vendre des ressources spatiales. Que ces lois fassent l'objet de clarification ou de contradiction est sujet à débat.

Traduit par la Traductrice

INTRODUCTION

Through centuries of scientific study and decades of space exploration, the presence of a range of potentially economic resources across the solar system has been established. Only recently has the prospect of harnessing these resources been considered a possibility. The act of harvesting, processing, and ultimately creating useful products from resources acquired in space can be described as space resource utilization (SRU). In recent years, various space agencies have been investigating one approach to SRU, namely in situ resource utilization (ISRU). As the name implies, ISRU entails using the resources encountered along the path of exploration to create products in support of the mission (Sanders and Larson 2015). SRU is not limited to the public sector. It is the opinion of some investors and industry professionals that SRU (e.g. Lewis 2014), and the hypothetical accompanying expansion of the space market, is a potentially industry-changing opportunity.

In order for SRU to be worthwhile for government space agencies, there must be a cost saving, a lowering of risk, or a mission enhancing benefit. For the private sector, profitability in a reasonably short time span following initial investment is a requisite. Considering the complexity of operations in space and the embryonic nature of the space market, this amounts to a substantial challenge. Undeterred, companies with the intentions of mining asteroids have already formed, including Planetary Resources and Deep Space Industries (recently acquired by Bradford Space). The governments of the U.S.A. and Luxembourg have demonstrated their support for SRU, passing legislation legalizing the sale of space resources (U.S. Commercial Space Launch Competitiveness Act of 2015; Government of Luxembourg 2017). While such legislation has not yet been passed in Canada, the Canada Mineral and Metals Plan, released by Natural Resources Canada in March 2019, recommends that the federal government should develop a policy approach for mining ‘new frontiers’ to foster investment and economic development (NRCan 2019). Space mining is explicitly acknowledged to be one of these new frontiers.

Due to their variety of resources, proximity to Earth, and attractiveness as exploration targets, previous work has identified the Moon, Mars and its satellites, and Near-Earth Asteroids (NEAs) as prime targets for SRU. The Moon is close to Earth, has various resources, and can serve as a proving ground for modern human exploration techniques prior to a human-crewed mission to Mars (e.g. Crawford 2015; Zuniga et al. 2015). SRU in the Martian system will likely be restricted to ISRU in support of Mars surface missions, and so less significant to the private sector (Mazanek et al. 2015); although SpaceX’s plans for Mars transportation infrastructure include the local production of rocket fuel on the Red Planet via ISRU. Finally, NEAs, the focus of the current study, offer rich and varied resources and are accessible; ~ 20% of NEAs have one-way rendezvous travel costs lower than the Moon (Benner 2018). The range of NEA compositions includes enrichments in base metals (e.g. Fe and Ni), semiconductors (e.g. Si), platinum group elements (PGEs), and volatiles, including water, C, N and S.

The goal of this study is not to argue the superiority of NEAs as potential resource hosts rather than say the Moon (Crawford 2015). Instead, we focus on NEAs due to their importance in the near-term of SRU. As well as being accessible, NEAs are enriched in a resource vital to the early development of SRU and the space market: water. This review will first explore the nature and distribution of asteroids and their meteorite offspring, informing the incidence, abundance, and grade of asteroid resources. The following sections will then explore the logistical feasibility, legal implications, and economic viability of asteroid mining. Lastly, it will discuss current ventures and Canadian opportunities in the field.

ASTEROID CHARACTERISTICS

Asteroids are typically relatively small, rocky bodies devoid of atmospheres that orbit the Sun. They range in size from almost 1000 km to 1 m in diameter (Rubin and Grossman 2010; Burbine 2016). Very broadly, they are composed of rock, metals, and volatiles in various combinations. Asteroids are divided into populations based on their orbits and reflectance spectra. The asteroids are numerous, but their combined mass is less than that of the Moon. The mass distribution of the asteroids is also uneven, with the largest asteroid, 1 Ceres, which is also classified as a dwarf planet, making up a third of the mass of the main belt asteroids alone (Hilton 2002).

Orbital Groups

There are three main orbital groups of asteroids. The main belt asteroids (MBAs) are the largest group of asteroids. They orbit the Sun at ~ 2.2 to ~ 3.2 au (astronomical unit; 1 au is the average distance from the Sun to the Earth), between the orbits of Mars and Jupiter. The focus of this review is on the NEAs, which are those asteroids that are no farther than 1.3 au from the Sun during their closest approach along their elliptical orbits (Shoemaker et al. 1979). The NEA population is subdivided into the Amors, Apollos, Atens, and Atiras (Fig. 1) (Shoemaker et al. 1979; Di Carlo et al. 2017). The Amors orbit the Sun outside of Earth’s orbit and never cross inside it. The Apollos are on average farther away from the Sun than Earth but cross into Earth’s orbit from the outside. Atens have shorter orbits than Earth but cross Earth’s orbit from the inside. Atiras are by far the least populous group and have shorter orbits than Earth and never cross its path.

The NEAs are more desirable for the near-term of SRU than other asteroid populations due to their relative proximity to Earth. The travel cost in space can be measured in units of speed. This parameter is called ΔV (pronounced ‘delta-vee’). Measured in kilometres per second, it is the change in velocity required to move from one location, or orbit, in space to another (Ross 2001). Because their orbits are so similar to Earth’s, the ΔV for one-way rendezvous from Low Earth Orbit (LEO) to ~ 20% of NEAs is less than the ΔV from LEO to the Moon (Benner 2018). Another consequence of Earth-like orbits is long synodic periods, i.e. the more similar a body’s orbit is to Earth’s, the longer the time period between closest passes. After rendezvous via optimal trajectory, the

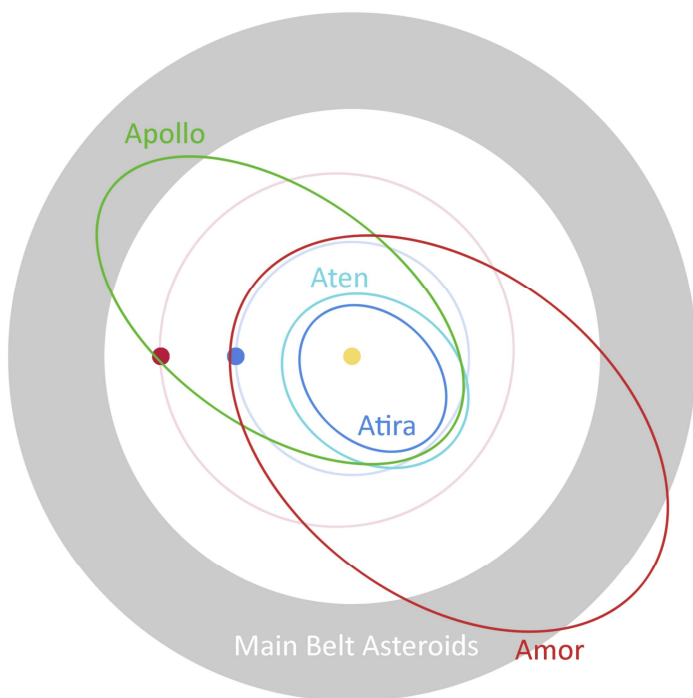


Figure 1. Near-Earth Asteroid orbital groups. The yellow, blue, and red circles designate the Sun, Earth, and Mars, respectively. The Amor asteroids have larger orbits than Earth and never cross its orbit. The Apollo asteroids have larger orbits than Earth but do cross its orbit. The Aten asteroids have smaller orbits than Earth and cross its orbit. The Atira asteroids have smaller orbits than Earth and never cross its orbit.

launch window for a minimum ΔV return trip is often many years or a decade later. Missions of shorter duration would have to budget for a non-optimal trip one way or another.

The third main family of asteroids is the Trojans. Jovian Trojan asteroids share the orbital path of Jupiter, residing in stable points $\sim 60^\circ$ preceding or trailing it. These are the L4 and L5 Lagrangian points respectively. To date, astronomers have discovered over 6,000 Jovian Trojans, but some estimate Jupiter's Trojans to be as numerous as the asteroids of the main belt (Yoshida and Nakamura 2005). Other planets with at least one known Trojan are: Venus (1), Earth (1), Mars (4), Uranus (2), and Neptune (17) (Connors et al. 2011; de la Fuente Marcos and de la Fuente Marcos 2014, 2017).

Another orbital group of potential interest are the Centaurs. These bodies orbit the Sun between the orbits of Jupiter and Neptune. Although more distant than the other groups they are thought to have intermediate characteristics between asteroids and comets, a hypothesis strengthened by the detection of various ices, including water and methanol (Cruikshank et al. 1998). These bodies could be optimal for fuelling activity in the outer solar system.

Spectral Types

In addition to orbital groups, asteroids are also classified by their reflectance spectra in the visible and infrared regions of the electromagnetic spectrum. Asteroids with similar reflectance have been interpreted to possess similar surface mineralogies and, therefore, similar compositions. However,

Table 1. Asteroid Spectral Classes. Taxonomies from Tholen (1984), Bus and Binzel (2002) and DeMeo et al. (2009).

Tholen (1984)	Bus and Binzel (2002)	DeMeo et al. (2009)
C-group (Carbonaceous)	C-complex (Carbonaceous)	C-complex (Carbonaceous)
B-type	B-type	B-type
C-type	C-type	C-type
F-type	Cg-type	Cb-type
G-type	Ch-type	Cg-type
	Cgh-type	Cgh-type
	Cb-type	Ch-type
X-group (Metallic)		
E-type	X-complex (Metallic)	X-complex (Metallic)
M-type	X-type	X-type
P-type	Xc-type	Xc-type
	Xe-type	Xe-type
Ungrouped	Xk-type	Xk-type
S-type (Silicaceous)		Xn-type
A-type	S-complex (Silicaceous)	
D-type	S-type	S-complex (Silicaceous)
T-type	Sa-type	S-type
Q-type	Sk-type	Sa-type
R-type	Sl-type	Sq-type
V-type	Sq-type	Sr-type
	Sr-type	Sv-type
	A-type	
	K-type	Ungrouped
	L-type	A-type
	Q-type	D-type
	R-type	K-type
		L-type
	Ungrouped	O-type
	T-type	Q-type
	D-type	R-type
	Ld-type	T-type
	O-type	V-type
	V-type	

factors such as the difficulty of modelling mineral absorption, regolith effects, and space-weathering, may cause objects with dissimilar mineralogies to have similar spectra and be incorrectly grouped together (Burbine 2016).

The colour of asteroids was first measured photographically by Bobrovnikoff (1929) but these measurements were too sparse and rudimentary to form the basis of a classification scheme. Chapman et al. (1975) put forth the first asteroid taxonomy and introduced the use of letters (C for carbonaceous, S for silicaceous), now a standard feature of all asteroid taxonomies. Next, Tholen (1984) proposed a new taxonomy consisting of 7 types in two groups and 7 more ungrouped types. They are the C-group (B-type, C-type, F-type, G-type), X-group (E-type, M-type, P-type), S-type, A-type, D-type, T-type, Q-type, R-type, and V-type. Like the Chapman et al. (1975) taxonomy, C-group are carbonaceous, and S-type are silicaceous or stony. The new X-group contains metallic asteroids, while the remainder have anomalous or intermediate characteristics (Table 1).

The next major overhaul of asteroid taxonomy stemmed from the Small Main-belt Asteroid Spectroscopic Survey (Bus and Binzel 2002; Burbine 2016) (Table 1). The SMASS system was designed to agree with previous classification schemes whenever possible. Thirteen of the 26 classes have single-letter names, with 12 taken from preceding taxonomies (A, B, C, D,

K, O, Q, R, S, T, V, and X) and one new class (L). The remaining 13 classes have lowercase modifiers to denote asteroids with intermediate spectral qualities. All but five of the classes are sorted into one of three complexes, broadly consistent with Tholen's groups. The taxonomy is as follows: C-complex (B-type, C-type, Cg-type, Ch-type, Cgh-type, Cb-type), S-complex (S-type, Sa-type, Sk-type, Sl-type, Sq-type, Sr-type and endmembers A-type, K-type, L-type, Q-type, R-type), X-complex (X-type, Xc-type, Xe-type, Xk-type), T-type, D-type, Ld-type, O-type, and V-type (Bus and Binzel 2002). The C, S, and X designations have the same meaning as in Tholen (1984).

The most recent iteration is the Bus-DeMeo taxonomy (DeMeo et al. 2009), which comprises 24 classes with a 25th Xn class being added after publication of the original paper (Burbine 2016). The class designations are nearly identical to those of Bus and Binzel (2002); only the Ld, Sl, and Sk classes were removed while the Sv and Xn classes were added (Table 1). Most bodies measured in both studies retained their classification. Those that did change mostly belonged to the S-complex subclasses (DeMeo et al. 2009). This taxonomy uses a 'w' at the end of certain classes to signify that the body has experienced space weathering. The taxonomy is as follows: C-complex (B-type, C-type, Cb-type, Cg-type, Cgh-type, Ch-type), S-complex (S-type, Sa-type, Sq-type, Sr-type, Sv-type), X-complex (X-type, Xc-type, Xe-type, Xk-type, Xn-type), A-type, D-type, K-type, L-type, O-type, Q-type, R-type, T-type and V-type (DeMeo et al. 2009).

Spectral Class Distribution

The differences in the mean albedo of asteroid spectral classes introduces discovery bias into the population of observed asteroids. Spectral classes with high average albedo (e.g. S-complex) are more readily discovered for a given diameter than asteroids with lower albedo (e.g. C-complex) (Fig. 2). The number of NEAs with spectral types is very low compared to the number of known NEAs (Carry et al. 2016). Thus, when considering the resource potential of the NEAs as a population, it is helpful to consider the debiased distribution, while bearing in mind that spectral data must be available for a specific asteroid for it to be considered as a potential mining target. Stuart and Binzel (2004) provide a bias-corrected distribution of spectral classes for NEAs by using a methodology that combines spectral and albedo data sets.

METEORITES AS ANALOGUES

Since no space agency has yet managed a sample return of more than a few micrograms of an asteroid (i.e. the Hayabusa mission), meteorites are the main samples of asteroid material currently available for study. However, the lack of spatial resolution and the aforementioned difficulties in interpreting asteroid spectra make meteorite-asteroid comparisons difficult, complicating the study of asteroid geology. Nevertheless, in the near-term, meteorites remain the best and only physical samples of asteroids available to scientists.

Meteorite Taxonomy

Meteorites are classified into chemical groups, each containing

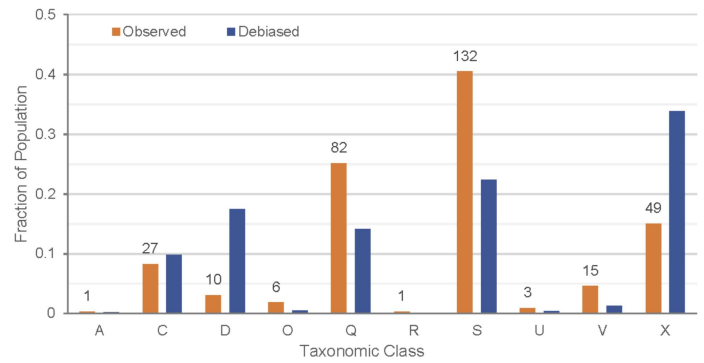


Figure 2. Observed and debiased distribution of taxonomic classes in the Near-Earth Asteroid (NEA) population. Observed data ($n = 326$) are from JPL Small-Body Database (accessed 05/06/18). For asteroids with both Tholen (1984) and Bus and Binzel (2002) classifications the latter took precedence. Some spectral classes were combined in accordance with the debiased estimations from Stuart and Binzel (2004). The numbers at the end of the orange columns are the total number of NEAs of that class in JPL Small Body Database.

rocks interpreted to be from a single parent body. The ultimate goal of meteorite classification is to couple each chemical group to its parent body in space. This goal has thus far proven elusive. The howardite-eucrite-diogenite (HED) clan of meteorites, thought to originate from the crust of asteroid 4 Vesta, is the only group of meteorites correlated with a specific asteroidal parent body (e.g. Consolmagno and Drake 1977). Except for a small number derived from the Moon and Mars, the majority of meteorites are derived from asteroids (Weisberg et al. 2006).

Traditionally, meteorites were divided into three categories based on composition alone: stony, stony-iron, and iron (Weisberg et al. 2006). Modern taxonomies incorporate their chemical, isotopic, compositional, and petrological nature to group samples that are genetically related (Weisberg et al. 2006). The first distinction made is the degree of differentiation of the parent body. Meteorites from undifferentiated bodies are called chondrites, named for the small (1–2 mm) silicate spheres called chondrules that they often, but do not necessarily, contain (Weisberg et al. 2006). Meteorites from differentiated bodies are called achondrites, primitive achondrites, or nonchondrites, depending on the taxonomy, and can be texturally altered but chemically primitive, partially melted, or fully differentiated. The literature contains numerous taxonomies that demonstrate no consensus on classification hierarchy, except for the final distinction of chemical group. For example, a particular specimen will belong to the same chemical group in all schemes, say an IIIAB iron, but that group could be deemed to be either a differentiated nonchondrite or an achondrite. For a thorough review of the subject the reader is referred to Weisberg et al. (2006).

Geological Processes

The geology of meteorites reflect geological processes that operated on the asteroid parent bodies. Such processes are responsible for the distribution of resources on asteroids. Perhaps most obvious is differentiation, with iron meteorites interpreted as representing core material and other meteorite classes, such as HEDs, representing crustal material (e.g.

Hutchison 2007; Elkins-Tanton and Weiss 2017). Chondrites show evidence of more localized processes, including thermal metamorphism, aqueous alteration, and shock metamorphism. Thermal metamorphism of increasing grade homogenizes the chemical composition of minerals, coarsens mineral grains at the expense of the matrix, before finally forming new minerals (Hutchison 2007). The parent bodies of meteorites displaying aqueous alteration warmed during accretion, but not enough to initiate thermal metamorphism. High water contents obtained from the solar nebula combined with this gentle heating led to the alteration of much of the olivine and pyroxene into hydrous phases in many meteorite classes (e.g. Hutchison 2007). This process created some of the most desirable asteroid classes from a resource perspective.

ASTEROID RESOURCES

Through asteroid spectroscopy and the study of meteorites, we know that asteroids contain a diverse array of resources including water (in hydrated minerals and ice), base metals, semiconductors, PGEs, and volatiles. For an asteroid resource to be considered for SRU, however, it must demonstrate mission enhancing or profit earning potential. A large part of the motivation for SRU is the potential cost savings of garnering resources required in space in situ. The additional expense associated with acquiring resources in space must be offset by the cost savings of reduced launch mass. With rocket launches out of the equation, the most cost-effective means of meeting demand on Earth will remain mining the planet itself. It follows that for any resource to be considered for SRU, at least in the short- to medium-term, there must be demand for it in space. Currently, the only resource with significant demand in space is water. A possible exception to this rule is the PGEs. They are sufficiently valuable that their import to Earth could be potentially economical in the future. Below, we discuss the short- and long-term potential of SRU from NEAs.

The Short Term

Excluding the engineering cost of extracting a target resource from an individual asteroid, the viability of an asteroid as a mining target is a function of its value and accessibility. An asteroid's value can be estimated as the product of its volume, density, concentration of the desired resource, and value of that resource. Its accessibility can be quantified as the minimum ΔV required for spacecraft rendezvous from LEO. For the purpose of the following parameterization, the minimum value that an asteroid must have to be considered a viable target will be set at \$1B, approximately the cost of an average interplanetary space exploration mission, and not far off the capital expenditure required to start a large mine on Earth.

Platinum Group Elements

PGEs are highly valued due to their scarcity, usefulness as catalysts, resistance to corrosion, and high melting points (Zientek and Loferski 2014). Except for the less valuable element, Ru, each element was valued between \$12,800 and \$35,600 USD kg⁻¹ (\$400 to \$1,100 USD/troy ounce) on average in 2017 (<https://apps.catalysts.basf.com/apps/eibprices/mp>). These

values are high enough that they may allow for economic extraction of PGEs from asteroids for the Earth market. The scarcity of PGEs is driven by their highly siderophile nature. During Earth's differentiation they partitioned strongly into the core, leaving the crust and mantle extremely depleted (McDonough and Sun 1995). What little PGEs that are found outside of the core are possibly the product of a late chondritic veneer (e.g. Schmidt 2004). Like Earth, some asteroids are also differentiated. Subsequent collisions have fragmented some of these bodies, thereby exposing their PGE-enriched core material. These are the metallic X-complex asteroids, thought to be largely composed of FeNi alloy, and are the likely parent bodies of iron meteorites (Burbine 2016).

The literature contains limited data on the full suite of PGE concentration in iron meteorites. Iridium concentrations are well studied, however, as they are used in iron meteorite taxonomy (Scott et al. 1973). For iron meteorites in general, PGE occurrence can be estimated as totaling seven times Ir abundance in CI chondritic ratios (Elvis 2014). A group of 71 iron meteorites from various chemical groups compiled in two papers have a mean concentration of 27 $\mu\text{g g}^{-1}$ total PGE (Wasson et al. 1989, 1998). Meteorites enriched in the 50th and 90th percentiles in the distribution contain 14 $\mu\text{g g}^{-1}$ and 68 $\mu\text{g g}^{-1}$ of PGEs respectively.

Asteroids are too small to be spatially resolved by ground-based telescopes. Instead, telescopic observations provide apparent magnitude (h), which is the brightness of an object as perceived by an observer on Earth. Apparent magnitude can then be used to calculate absolute magnitude (H), which is the brightness of an object as it would be seen from a standard distance. From H , and an assumed average albedo for NEAs of 0.14, asteroid diameter is calculated. Lastly, volume is determined assuming a spherical shape. While virtually all asteroids are not spherical, this assumption is made considering that the diameter calculated will be intermediate between the asteroid's long and short axes, resulting in a reasonable approximation of asteroid volume. There appears to be no correlation between absolute magnitude (H) and taxonomic class in the NEA population (Stuart and Binzel 2004); i.e. taxonomic classes are uniformly dispersed throughout the size range of NEAs.

The density of metallic asteroids remains poorly constrained. Iron meteorites have densities of $\sim 7900 \text{ kg m}^{-3}$ but asteroids, particularly those of small mass ($< \sim 10^{20} \text{ kg}$), are expected to have significant porosity (Henderson and Perry 1954; Carry 2012). Only considering asteroid densities of reasonable accuracy, and those from X-complex subclasses with densities indicative of metallic composition (Xc and Xk, ρ_{50} from Table 3 in Carry 2012), yields a mean density of 4 000 kg m^{-3} for 12 asteroids.

'Average' (50th percentile PGE concentration) and 'good' (90th percentile) metallic asteroids reach values of \$1B at diameters of 119 m and 71 m respectively. As volume and, therefore, mass scales with the cube of the radius, asteroids of increasing size rapidly increase in value. A 240 m diameter asteroid would be worth \$8.2B and \$39B in the average and good cases, respectively (Table 2). Accordingly, asteroids lose their value with decreasing size just as rapidly. Asteroids of 100

Table 2. Value of Platinum Group Elements (PGEs) in metallic asteroids.

Diameter (m)	Mass (kg)	PGE Concentration (ppm)	PGE Value (\$ / kg)	Value of asteroid (\$M)
100	2.09E+09	14.28	19,903	\$595
120	3.62E+09	14.28	19,903	\$1,029
160	8.58E+09	14.28	19,903	\$2,438
240	2.90E+10	14.28	19,903	\$8,229
60	4.52E+08	67.66	19,903	\$609
75	8.84E+08	67.66	19,903	\$1,190
120	3.62E+09	67.66	19,903	\$4,874
240	2.90E+10	67.66	19,904	\$38,989

and 60 m diameter are only worth ~ \$0.6B in the average and good cases, insufficient to warrant a mining venture (Table 2).

Of the 326 asteroids with a spectral classification in the JPL Small-Body Database, 15% ($n = 49$) are X-complex. This is a small fraction of the total known NEA population and does not account for discovery bias favouring higher albedo asteroids, particularly S-complex, over the lower albedo C and X-complexes (Stuart and Binzel 2004). The debiased depiction of the taxonomic distribution of NEAs of Stuart and Binzel (2004) indicate that 34% of NEAs belong to the X-complex. Due to the paucity of spectral type designations among known NEAs, the debiased fraction will be used for subsequent inferences made in this section.

Neeley et al. (2014) compared infrared and visible observations of 29 X-complex asteroids to meteorite spectra. They mainly targeted Xc- and Xk-types, as they are devoid of any strong spectral features, indicative of FeNi metal. Eighteen of the asteroids also had radar data available. Of these, 22% ($n = 4$) were determined to be analogous to iron meteorites by both the radar data and at least one of the two methods employing spectral data (Neeley et al. 2014). In the paper that introduced their taxonomy, DeMeo et al. (2009) classified 32 X-complex asteroids of which 66% ($n = 21$) were either Xc- or Xk-type.

In summary, the fraction of X-complex NEAs is 0.34, the fraction of X-complex asteroids that are Xc- or Xk-type is 0.66, and the fraction of Xc- and Xk- types that are metallic is 0.22. The product of these numbers reveals ~ 5% of NEAs are expected to be metallic. As mining missions will require heavy payloads both to and from the asteroid, targets with low ΔV are prioritized. Elvis (2014) suggests a maximum ΔV of 4.5 km s⁻¹ for the accessibility cut off, as this figure at least doubles the payload capacity versus a mission to a median NEA (6.65 km s⁻¹). Only 1.4% of the 17,607 NEAs have $\Delta V \leq 4.5$ km s⁻¹ (Benner 2018).

Adapting the approach taken by Elvis (2014), the fraction of NEAs that are expected to be prospective PGE sources is

$$\begin{aligned} P_{NEA-PGE} &= P_{type} P_{cnt} P_{\Delta V}, \\ &= 0.05 \ 0.50 \ 0.014, \\ &= 0.00035 \end{aligned} \quad (\text{Eq. 1})$$

where P_{type} is the fraction of metallic asteroids, P_{cnt} is the fraction of asteroids with favourable PGE concentrations (in this

Table 3. Value of water in C-complex Near-Earth Asteroids.

Diameter (m)	Mass (kg)	Water Concentration (wt %)	Water Value (\$ / kg)	Value of asteroid (\$M)
8	3.78E+05	16	5000	\$302
12	1.28E+06	16	5000	\$1,021
16	3.02E+06	16	5000	\$2,419
50	9.23E+07	16	5000	\$73,827

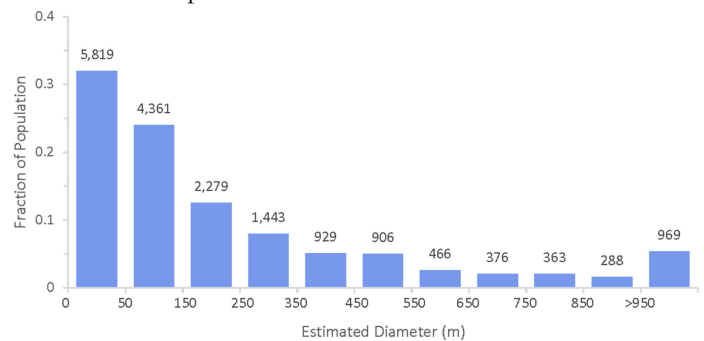
case 50th percentile or better), and $P_{\Delta V}$ is the fraction of accessible asteroids. By this metric, 0.035%, or approximately 1 out of every 2900 NEAs are prospective for PGEs. Using an assumed average albedo of 0.14, the number of known NEAs with $D \geq 119$ m is 907 (CNEOS 2018). The product of these numbers reveals that three members of the known NEA catalogue are expected to be potentially viable PGE sources. While this may seem bleak, it is mostly limited by the stringent ΔV requirement. If propulsion technology advances enough to facilitate missions with $\Delta V \leq 5.5$ km s⁻¹, the number of prospective asteroids increases to 25 (~ 1/350).

These estimates are based on the currently known fraction of the NEA population (Fig. 3). The size distribution of the entire NEA population can be estimated by a simple power law (Stokes et al. 2003). The function is

$$N(> D(km)) = 942D^{2.354} \quad (\text{Eq. 2})$$

where N is the cumulative number of NEAs above a given diameter D . From the power law there are expected to be 141,323 NEAs with $D \geq 119$ m. This increases the number of prospective NEAs for PGEs to 49 at $\Delta V \leq 4.5$ km s⁻¹ and 403 at $\Delta V \leq 5.5$ km s⁻¹.

An important consideration is the effect of increased supply on PGE value. An estimated 560,000 kg of PGEs were produced from mined and recycled sources globally in 2016 (NRCAN 2018). A \$1B asteroid contains 50,200 kg PGEs. While price does not scale linearly with supply, adding 10% to the global supply would likely depress the price to some extent. A \$10B asteroid would contain nearly the entire annual PGE production, depressing prices even further. This effect is possibly alleviated by selling asteroid derived PGEs over an extended time span.

**Figure 3.** Size distribution of known Near-Earth Asteroids (NEA). Diameter estimates are calculated from absolute magnitude (H) using an assumed average albedo (a) of 0.14. Absolute magnitudes are from JPL Small Body Browser, current as of 21/05/18. The number of NEAs in each bin is labeled on the end of the columns.

The above estimates do not account for the engineering cost of PGE extraction. While this is difficult to directly estimate, the value per tonne of asteroid material compared to ores on Earth can shed light on the potential extraction budget. Earth's highest-grade PGE ores are located within the Stillwater Complex, Montana. The most enriched zone of the complex is the J-M reef. A 5.5 km long and 2.1 m thick section of this zone contains PGE values of ~\$550 USD/t in Pt and Pd (Todd et al. 1982). The reserves here are small relative to South Africa's Bushveld Complex, the world's largest producer. The South African ore was worth ~\$100 USD/t in Pt, Pd, Rh, Ru, Ir, and Au in 2015 (Thormann et al. 2017). In contrast, 50th and 90th percentile metallic asteroids would be worth ~\$280 USD/t and ~\$1350 USD/t, respectively.

Considering the relative grades and the increased complexity of space-based PGE extraction, the engineering costs may dictate that only highly concentrated metallic asteroids can be considered as mining targets, or that PGE production from asteroids will only be economical as a by-product of another process. The logistical feasibility of PGE production from NEAs is explored in the following section.

Water

Unlike PGEs, water is a strategic resource in the short term of NEA SRU due to its existing demand in space. To be economical, water must be more cost-effective to source and process it from NEAs than launch it from Earth. The value of water in space is derived from its vast array of potential applications. Most importantly in the short term, it can be electrolyzed into its constituent hydrogen and oxygen, which upon recombination create an exothermic reaction that can be harnessed for rocket propulsion. It can also be used for radiation shielding, growing plants, for breathing (O₂ from electrolysis) and, of course, drinking for humans. Presently, the market for water in space is delivery to the International Space Station and as propellant for satellite station-keeping (Sommariva 2015). In the near future, the advent of a cis-lunar (located in between Earth and the Moon) propellant depot and a fleet of satellite-servicing space-tug vehicles could considerably increase demand (Metzger 2016). A cis-lunar propellant depot would reduce costs faced by government agencies and private companies, lowering the barrier to entry for space operations, and stimulating activity in the space market. Space-tug vehicles, operated independently or by the asteroid mining corporations themselves, could rapidly transport satellites from LEO to geostationary orbit (GEO), saving satellite operators from lost profits accrued over the months it takes to deploy communications satellites via ion propulsion (Metzger 2016).

Moving forward, an important potential application of water in space is for radiation shielding. Of the types of radiation prevalent beyond Earth's magnetosphere, galactic cosmic rays and solar particle events pose the greatest risk to human health (Cucinotta and Durante 2006). Together, they are the source of all cosmic radiation (Sihver 2008). Unlike other forms of radiation (e.g. gamma rays) cosmic rays are not most effectively shielded by dense, high atomic mass materials (Sihver 2008). Their interaction with these materials produces

secondary radiation, in some cases to the effect of increasing the total intensity. Liquid hydrogen is the most effective shield against cosmic radiation, with low atomic mass hydrogen-bearing compounds, such as water, also performing well (Sihver 2008). Water is much simpler to store than liquid hydrogen, and large reservoirs would be required for hydration at any rate, making it the logical choice for radiation shielding.

As was the case for PGEs, the portion of asteroids prospective for water extraction can be estimated using the methods of Elvis (2014). Water is expected to be found in the highest concentrations on C-complex asteroids (Ross 2001), in hydrated phyllosilicates and in subsurface ice. Accounting for discovery bias, 9.8% of NEAs are estimated to be C-complex (Stuart and Binzel 2004).

The contribution of hydrated phyllosilicates to the water content of C-complex asteroids can be estimated from knowledge of meteorites. A study by Jarosewich (1990) compiled chemical analyses determining water content in 22 carbonaceous chondrite samples. Removing the duplicate analyses (three measurements of Murchison and the pair of ALH 83100 and ALH 83102) leaves 19 chondrites with a mean water content of 3.9 wt.%. Eleven of these have < 2 wt.% H₂O (~58%) and six (32%) have > 6 wt.% H₂O (Jarosewich 1990). This higher group will be considered the portion of C-complex NEAs enriched in water. Elvis (2014) used 10 wt.% H₂O as the contribution of hydrated phyllosilicates to the water content of C-complex asteroids. However, given it is unlikely that all the H₂O can be extracted, the current study will use this more conservative value of 6 wt.%.

The contribution of subsurface ice to the total water content is harder to estimate. Carbonaceous chondrites have porosities of 1–20% while C-complex NEAs have macro-scale porosities of 28–60% (Carry 2012; Elvis 2014). This leaves large volumes to be potentially occupied by water ice and other volatiles, but without prospecting spacecraft it is impossible to know the contents of the voids. Elvis (2014) estimated 10 wt.% H₂O as subsurface ice, a value which shall also be used in the current study.

The fraction of NEAs prospective for water is then

$$\begin{aligned} P_{NEA_{Water}} &= P_{type} P_{cnc} P_{\Delta V} \\ &= 0.098 \cdot 0.32 \cdot 0.014, \\ &= 0.00044 \end{aligned} \quad (\text{Eq. 3})$$

when using the same accessibility cut off as before. This is equivalent to about 1 in 2300 NEAs. Carry (2012) gives reasonably accurate densities for 19 C-complex asteroids with a mean density of 1410 kg m⁻³ (ρ_{50} , Table 3 in Carry 2012). If water can be sold in space for \$5000 kg⁻¹, half of the historical cost of launching a kilogram of mass into LEO, a NEA as small as 12 m is worth over \$1B (Table 3). There are 17,371 known NEAs of $D > 12$ m for a total of seven NEAs prospective for water (Fig. 3). Increasing the minimum ΔV by 1 km s⁻¹ brings the total to 62 NEAs. The validity of the figure selected for the value of water in space is discussed in the following section.

There are expected to be vastly more NEAs of small size (< 50 m) than currently known (Fig. 3). There are 4991 known

Table 4. Resources in asteroids, adapted from Sanchez and McInnes (2013).

Resource	Asteroid Class	Fraction of NEA swarm	Resource mass fraction	Space-based application	Resource mass in 120 m asteroid (t)
Fe, Ni, Co	metallic X-complex ¹	0.05	95 wt % ³	Infrastructure material	3,438,156
PGEs	metallic X-complex ¹	0.05	68 ppm	Import to Earth, electronics	245
Semiconductors	metallic X-complex ¹	0.05	1,600 ppm ⁴	Electronics (e.g. solar panels)	5,791
H ₂ O	water-rich C-complex	0.03	16 wt %	Propellant, radiation shielding, hydration, hygiene, respiration (O ₂ - electrolysis), space resource refinement, agriculture	255,147
N ₂	C-complex	0.10 ²	934 ppm ⁵	Atmosphere, fertilizer	1,192
Silicates	S-complex	0.22 ²	70 wt % ⁶	Agriculture, radiation shielding	1,710,030
Organics	C-complex	0.10 ²	4,000 ppm ⁷	Agriculture	5,103

Resources are listed with their asteroid class of highest concentration but may be found in other classes as well. Organics refers to organic molecules only, bulk C content is expected to be considerably higher. Fraction of Near-Earth Asteroid (NEA) swarm and resource mass fraction are from the text unless otherwise noted. ¹Based on iron meteorites with 90th percentile Ir enrichment; ²(Stuart and Binzel 2004); ³(Wasson 1974); ⁴(Kargel 1994; Ross 2001); ⁵(Alexander et al. 2012; average of CM chondrites from the supplementary material); ⁶(McSween et al. 1991); ⁷(Botta and Bada 2002).

NEAs 12–50 m in diameter, but from the power law there are expected to be 3×10^7 NEAs in this size range. This brings the total number of NEAs prospective for water to $\sim 13,000$ at $\Delta V \leq 4.5 \text{ km s}^{-1}$ (Stokes et al. 2003).

Another possible reservoir of water on asteroids is surficial water ice. It is expected to be rare on asteroids due to the rate of sublimation close to the Sun but it has been detected independently by two teams on asteroid 24 Themis (Campins et al. 2010; Rivkin and Emery 2010). Ceres, a C-complex asteroid and the solar system's largest, is one of two targets of NASA's Dawn mission. Dawn began orbiting Ceres in March 2015 and continued to do so until November 1, 2018. In this time, it generated global maps using its framing camera and visible and infrared mapping spectrometer as well as gathered elemental data with its Gamma Ray and Neutron Detector. From these data it has been estimated that Ceres contains $\sim 17\text{--}30 \text{ wt.}\%$ H₂O, has rare surface water ice, and that ice has remained within a metre of the surface for the body's lifetime (Prettyman et al. 2017).

The Long Term

As time progresses, the maturation of SRU and the cis-lunar economy will allow for increasingly diverse ventures. The array of resources available in asteroids could potentially permit opportunities including more ambitious and frequent space exploration missions, space tourism, and possibly a permanent human presence in space. Key resources for this level of development include base metals, semiconductors, and life-sustaining volatiles (Table 4). Sourcing and manipulating base metals such as iron in space would permit the fabrication of infrastructure at scales unhindered by the need to escape Earth's gravity well. Semiconductors are ubiquitous in modern elec-

tronics and their presence in asteroids would allow the fabrication of electronics in space. A promising application is to build enormous solar panel arrays in orbit (e.g. Glaser 1977; Sanchez and McInnes 2013). Here, the collection of energy is independent of weather conditions and the scale of the array is not limited by the need for the structure to support its own weight. The energy collected can be used in space or perhaps even transmitted back to Earth (Glaser 1977). Asteroids also contain volatile elements like C, N, P, and S, all of which are required by human metabolism. Nitrogen is particularly important because it is needed as an inert atmospheric component as well as a source of nutrition.

LOGISTICS

The logistical challenges of asteroid mining are varied, complex, and often without precedent. This section will illustrate the stages involved in asteroid mining from initial discovery to final product. Proven technologies and methods will be presented when possible, although many aspects of this section will be speculative in nature.

Many logistical specifics will change on a case by case basis depending on factors such as mission architecture, target resource, target asteroid, etc., but the process can be broadly divided into three major categories: 1) Discovery and Characterization; 2) Harvesting and Transportation; and 3) Extraction (Fig. 4). The first phase, Discovery and Characterization, describes the progression from asteroid discovery to target selection. Next, Harvesting and Transportation, deals with the retrieval and relocation of asteroid material. The final phase, Extraction, describes a collection of processes used to make finished products from raw asteroid material. The phases are presented as such for ease of communication but in practice

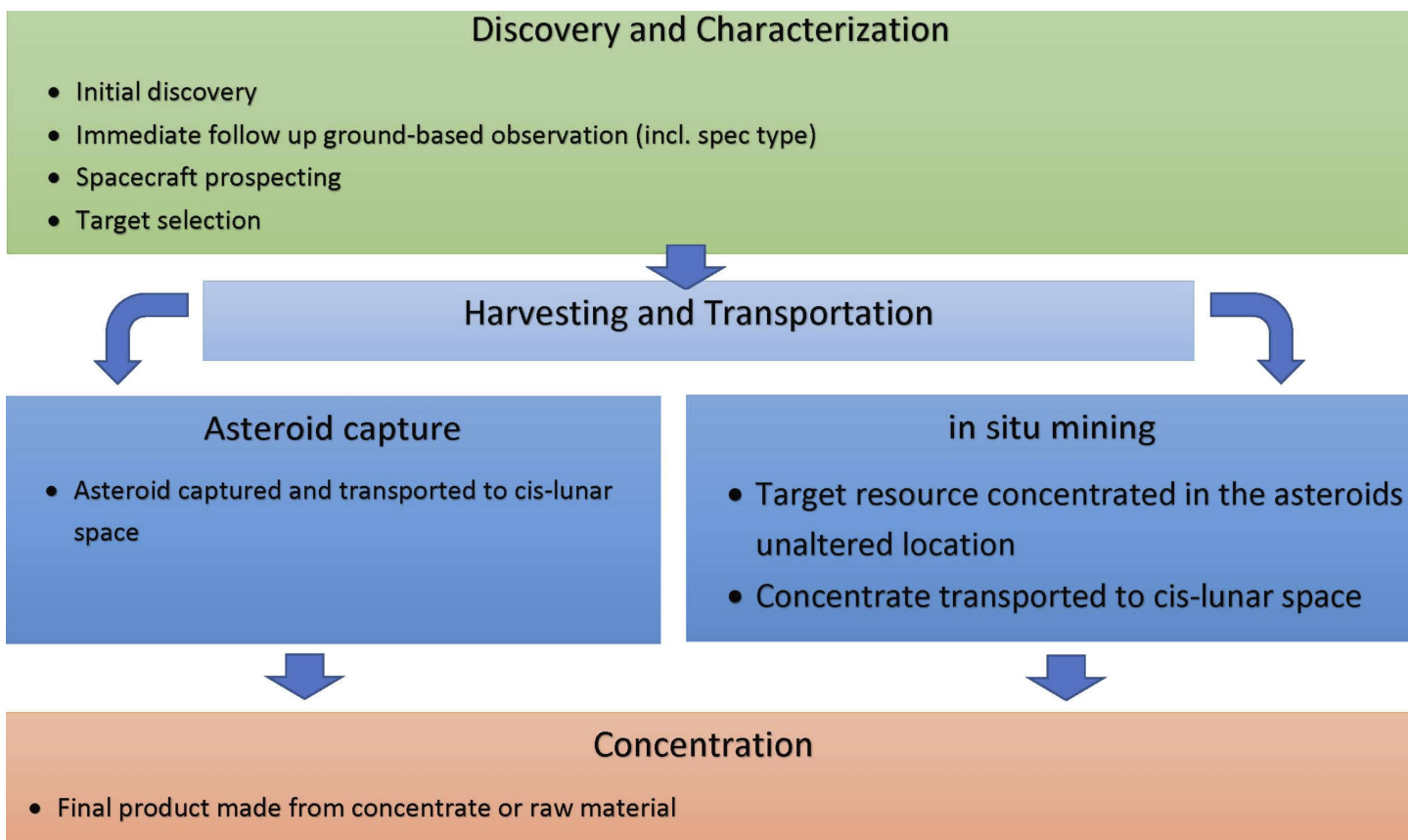


Figure 4. Stages of asteroid mining logistics. See text for details.

the boundaries between them, particularly the final two phases, will likely not be so clear-cut.

Discovery and Characterization

NEAs are continually discovered and catalogued by numerous organizations for reasons of scientific interest and as an attempt to identify potentially Earth impacting bodies. NASA’s Jet Propulsion Laboratory (JPL) runs the Center for Near Earth Object Studies (CNEOS), which supports many discovery surveys at institutions throughout the United States. The five NASA-supported surveys that discovered at least a single new NEO in 2017 are the Catalina Sky Survey (991; Tucson, Arizona), Pan-STARRS1 (893; Maui, Hawaii), ATLAS (98; Hawaii), LINEAR (22; Socorro, New Mexico), and NEO-WISE (26; spacecraft in polar orbit) (CNEOS 2018). Of the 18,000+ known NEOs only 107 are comets. NEOs are discovered by taking telescopic photographs of the same area of the night sky several minutes apart (Steel 2001). Distant stars and galaxies remain in the same relative location in the photographs, but nearby objects do not (Wainscoat et al. 2016).

After ground-based observation provides a robust catalogue of NEA characteristics (size, orbital elements, spectral type) prospecting spacecraft will be deployed to the most promising asteroids to finely characterize them before the investment of a full-scale mining mission is made. There is precedent for spacecraft observation of asteroids. Including NASA’s Dawn mission, there are 12 past or ongoing missions

visiting 14 asteroids with five more in the planning or concept stage (Table 5). Current spacecraft asteroid observations total 3 NEAs and 11 main-belt asteroids. Even with NASA and JAXA’s growing interest in asteroid missions, the scale of space borne asteroid observations required for efficient prospecting requires hands-on solutions from the would-be asteroid miner.

The spacecraft will take measurements of size and shape, density, structure, composition, and resource distribution. This can be accomplished with on-board sensors including cameras and spectrometers. These spacecraft may also include assay probes to directly sample the surface/shallow subsurface of promising regions. A single spacecraft will have to be deployed for each potential target, dictating lightweight and inexpensive design to enable multiple simultaneous deployments from a single launch vehicle.

Since only 1 in ~ 2900 and 1 in ~ 2300 NEAs are potential PGE and water sources respectively, and the prospect deploying thousands of space probes is clearly unfeasible, the need for enhanced ground-based characterization of NEAs with an emphasis on spectral class determination and small body discovery (for water-bearing NEAs) is very apparent.

Harvesting and Transportation

The two aspects of this phase are grouped together in acknowledgement of variable mission architectures and despite their different technological requirements. The first



Table 5. Successful and forthcoming asteroid exploration missions.

Mission Status	Mission Name	Agency	Launch Date	Completion Date	Asteroid Target(s)	Mission Type
Complete	Galileo ¹	NASA	18-Oct-89	21-Sep-03	Gaspra, Ida	both Flyby
	NEAR - Shoemaker ²	NASA	17-Feb-96	28-Feb-01	Mathilde, <i>Eros</i>	Flyby, Orbit
	Cassini ³	NASA/ESA	15-Oct-97	15-Sep-17	Masursky	Flyby
	Deep Space 1 ⁴	NASA	24-Oct-98	18-Dec-01	Braille	Flyby
	Stardust ⁵	NASA	07-Feb-99	15-Jan-06	Annefrank	Flyby
	Hayabusa ⁶	ISAS	09-May-03	13-Jun-10	<i>Itokawa</i>	Orbit/Sample return
	Rosetta ⁷	ESA	02-Mar-04	30-Sep-16	Šteins, Lutetia	both Flyby
Ongoing	New Horizons ⁸	NASA	19-Jan-06	2038	APL	Flyby
	Dawn ⁹	NASA	27-Sep-07	late 2018	Vesta, Ceres	both Orbit
	Chang'e 2 ¹⁰	CNSA	01-Oct-10	2029	<i>Toutatis</i>	Flyby
	Hayabusa2 ¹¹	JAXA	03-Dec-14	01-Dec-20	<i>Ryugu</i>	Orbit/Sample return
	OSIRIS-REx ¹²	NASA	08-Sep-16	24-Sep-23	<i>Bennu</i>	Orbit/Sample return
Planned	NEA Scout ¹³	NASA	15-Dec-19	2023	<i>1991 VG</i>	Flyby
	Lucy ¹⁴	NASA	Oct-21	2033+	<u><i>Eurybates</i></u> , <u><i>Polymele</i></u> , <u><i>Leucus</i></u> , <u><i>Orus</i></u> , <u><i>Patroclus</i></u> , <u><i>Donald-johanson</i></u>	all Flyby
	DESTINY+ ¹⁵	JAXA	2022	2026+	<i>Phaethon</i>	Flyby
	Psyche ¹⁶	NASA	2022	arrive 2026	<i>Psyche</i>	Orbit
	AIDA ¹⁷	NASA/ESA	2021 and 2023	arrive 2022 and 2026	<i>Didymos</i>	Impact and Orbit

Missions with titles in bold have asteroids for primary targets. Asteroid names in italics are near-Earth asteroids, main belt is in normal text, and trojans are underlined. All dates 2018 and onwards are projected and subject to change. Completion dates for Stardust and Hayabusa are the dates of sample canister reentry. ¹(JPL 2018a); ²(NASA 2018b); ³(JPL 2018b); ⁴(JPL 2018c); ⁵(JPL 2018d); ⁶(JPL 2018e); ⁷(ESA 2018a); ⁸(JHU/APL 2006); ⁹(JPL 2018f); ¹⁰(ESA 2018b); ¹¹(JAXA 2018); ¹²(NASA 2018a); ¹³(Mahoney 2018); ¹⁴(Garner 2017); ¹⁵(Kruger 2017); ¹⁶(JPL 2018g); ¹⁷(ESA 2018c).

decision of this phase is the extent to which material will be concentrated prior to transport. Previous authors have suggested two approaches; “asteroid capture” and “in situ mining” (Probst et al. 2016). In the former, asteroids, in entirety or in part, are captured and transported to a designated location for subsequent resource extraction. In the latter, asteroid resources are concentrated or extracted in the unaltered orbit of the asteroid prior to transport. In situ mining allows for more efficient transport at the cost of increased reliance on autonomy; the communication delay between Earth and NEAs is often several minutes each way. Asteroid capture would enable near real-time manoeuvres and shorter delays between extraction and sale, allowing operations to respond to changes in demand. This comes at the cost of decreased transportation efficiency and increased propulsion needs.

Depending on the target resource, the degree of autonomy required to run a mining operation, including troubleshooting and mitigating unexpected events, is beyond the capabilities of current technology, leading some researchers to suggest asteroid capture is the only viable option (e.g. Mazanek et al. 2015). While technologically feasible at small scales, asteroid capture’s efficiency is severely limited by the maximum possible mass retrieved. It is important to note that the complexity of resource extraction depends on the target resource and asteroid. Extraction of volatiles, like water, from rocky or rubbly asteroids is presumably a simpler task than the extraction of precious metals from a monolithic asteroid of solid FeNi alloy. The former may even be within the capabilities of current autonomous robotics (Trans Astronautica Corporation:

<http://www.transastracorp.com>). The estimates below will account for transportation only and not the engineering cost of harvesting and/or concentration the target resource.

A study by Brophy et al. (2012) investigated the feasibility of capturing a boulder from a large NEA, or an entire small NEA, and bringing it to cis-lunar space. They found that current propulsion technology can transport a 7 m diameter asteroid of ~ 500 t from a favourable orbit to cis-lunar space in ~ 10 years. The study estimated the cost of such a venture to be ~ \$2.6B. This estimate was based on the orbit of asteroid 2008 HU4, the eighth most accessible of all known NEAs with a ΔV of 3.91 km s⁻¹ (Benner 2018). Operations at asteroids with ΔV s of up to 4.5 km s⁻¹ will be more expensive. It should also be noted that the Brophy et al. (2012) study includes a 30% (\$611B) buffer for reserves.

Transporting 500 t of material from a NEA in a favourable orbit to cis-lunar space for \$2.6B is equivalent to \$5294 kg⁻¹ (Brophy et al. 2012). This figure includes research, development, spacecraft testing, and the price of the launch vehicle. Removing all but the recurring costs from this estimate yields an expense of \$2634 kg⁻¹ to transport asteroid material into cis-lunar space.

If the value of water in space is assumed to be \$5000 kg⁻¹, a 90% pure concentrate is worth \$4500 kg⁻¹ and unprocessed asteroid material at 16 wt.% is worth \$800 kg⁻¹. With the same 90% extraction rate, the material’s value is \$720 kg⁻¹. Accounting for the cost of transport, the concentrate provides net gains of \$1866 kg⁻¹ and the non-concentrated material incurs losses of \$1914 kg⁻¹. The case for in situ concentration is,

therefore, strong, unless advances in propulsion technology can reduce transport costs by a factor of ~ 4 . It is important to note that the value of water in space is estimated to be half of $\$10,000 \text{ kg}^{-1}$, the canonical cost of launching mass from Earth's surface to LEO. The validity of this figure could soon change due to recent innovations in the commercial space launch sector. For example, SpaceX's Falcon 9 can bring payloads to LEO for $\$2719 \text{ kg}^{-1}$ and their Falcon Heavy is purported to do the same for $\$1411 \text{ kg}^{-1}$, although the latter has only a single test flight to date (<http://www.spacex.com/about/capabilities>). The rockets are advertised to deliver mass to geosynchronous transfer orbit (GTO) for $\$7470 \text{ kg}^{-1}$ and $\$3371 \text{ kg}^{-1}$ respectively. If SpaceX's Falcon Heavy matures into a reliable technology, it represents a significant decrease in the value of resources in space. Similar degrees of innovation will have to be made in the production of asteroid resources to ensure a competitive advantage.

Extraction

In this, the final phase, resources are (further) concentrated and processed into final products. The following methods are conceptual in nature but draw on proven technology when possible.

Water can be extracted from asteroids by thermal dehydration of phyllosilicate minerals (e.g. King et al. 2015). Trans Astronautica Corporation (TransAstra) is a Los Angeles based company developing its own method of thermal dehydration called optical mining (https://www.nasa.gov/directorates/spacetech/niac/2017_Phase_I_Phase_II/Sustainable_Human_Exploration/). Its concept is to use concentrated sunlight and a containment bag to simultaneously extract volatiles and excavate the asteroid. In a full-scale test using a synthetic CI-like asteroid and a 10 m diameter solar collector they successfully demonstrated their technology. As predicted, the escaping volatiles caused the host rock to fracture, continually exposing fresh surfaces. Once liberated, the volatiles can be separated and purified by fractional distillation.

Most NEAs are understood to be "rubble-piles" or unconsolidated rock fragments held together by electrostatic, Van der Waal, and gravitational forces (Daniels 2013; Mazanek et al. 2015). A popular suggestion is to concentrate metallic phases by combing their surfaces with an electromagnetic rake (Kargel 1994).

Biomining techniques use microbes to extract metal from ores. Globally, $\sim 20\%$ of copper and $\sim 5\%$ of gold are extracted via biomining (Johnson et al. 2013). A paper by Klas et al. (2015) explores the feasibility of utilizing biomining on asteroids. The authors suggest extremophiles – microorganisms resistant to extremes in temperature, pressure, pH and radiation – may be of potential use for space-biomining applications. All are dependent on the presence of liquid water, however, so construction of an enclosed volume in which an appropriate temperature and atmosphere can be maintained is required. In addition to metal extraction, some microbes are also capable of methanogenesis (Klas et al. 2015). These microorganisms consume compounds like acetate, hydrogen, and carbon dioxide, materials found in carbonaceous asteroids,

and produce methane. This simple hydrocarbon is a viable alternative to liquid hydrogen for rocket propellant as it is nearly as efficient, less hazardous, and allows for denser and warmer storage. Klas et al. (2015) suggest that the high surface area to volume ratio of rubble-pile asteroids is advantageous for biomineralization, because of both increased exposure and the unconsolidated nature that provides natural radiation shielding for deeply penetrating microbes.

While originally demonstrated on nickel oxides, the Mond process can also be used to purify metals from alloys. First described in 1890, the process uses carbon monoxide to form nickel carbonyl (NiCO_4) which is then decomposed to form pure nickel, impure residue, and carbon monoxide (Mond et al. 1890). The resultant nickel can be deposited onto a substrate or as a powder. Other metals like iron and chromium also form carbonyls and can be similarly extracted. Iron and nickel can be used for structural fabrication and 3-D printing (from their powders) while the residues will be PGE-enriched.

When considering the logistics of space-based resource production it is also prudent to consider the environmental impact. On the one hand, moving a portion of resource production into space reduces the quantity of waste and pollutants that must be accommodated by the Earth (Hlimi 2014). Further, if production is fully automated then the risk to human health associated with the use of chemicals like nickel carbonyl can be negated. In the long-term, minerals important to renewable energy production could be sourced from NEAs, reducing the cost of renewable energy technologies (Metzger 2016). At some point it may even be possible to generate solar power in space for use on Earth while adding zero carbon to our atmosphere (Metzger 2016).

On the other hand, there are legal and ethical concerns regarding the contamination of asteroid material. Pristine asteroid material has high scientific value (e.g. NASA 2018b); processing large quantities of asteroid material for economical benefit could potentially destroy clues regarding the nature and evolution of our solar system that lay previously unspoiled for more than four billion years. The legal implications of contaminating extraterrestrial material is discussed below. A resource production scheme that removes a substantial portion of an asteroid's mass also has the potential to alter its orbit, necessitating great care as to not inadvertently send an asteroid on a collision course with Earth. There is also concern that any form of increased activity in space will contribute to the growing problem of space debris, fragments of anthropogenic material, particularly those that orbit the Earth that can cause destructive impacts with satellites and spacecraft (Hlimi 2014). As with resource production on Earth, asteroid mining missions must predict and minimize any deleterious effects on the surrounding environment.

ASTEROID MINING AND THE LAW

In addition to the logistical challenges of asteroid mining, one must also consider the legal implications. Early space legislation was drafted at a time when space was the exclusive domain of governmental bodies and so little thought was given to the potential commercialization of space and asteroid mining.

More recently, some governments have made efforts to encourage private sector involvement in space resources, but complications persist.

International Space Law

The history of space policy begins with the creation of the Committee on the Peaceful Uses of Outer Space (COPUOS) by the United Nations General Assembly in 1958. Made permanent the next year, the Committee was formed to “*govern the exploration and use of space for the benefit of all humanity: for peace, security and development*” (COPUOS 2017a). Originally consisting of 18 members, COPUOS now has 84, including all major spacefaring nations. COPUOS was pivotal to the creation of the five treaties and the five principles that govern the exploration of outer space (COPUOS 2017a). The first and most influential of the treaties is the “Outer Space Treaty” of 1967. Of the remaining treaties and principles, the “Moon Agreement” of 1984 is most pertinent to SRU.

The Outer Space Treaty

The Outer Space Treaty (OST) is the most fundamental piece of space legislation produced to date. Officially named the *Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies*, the treaty entered into force on October 10, 1967 after it was ratified by the three depository governments of the United States, the Soviet Union, and the United Kingdom (COPUOS 2017b). The Treaty contains 27 articles. The first 12 directly govern the exploration and use of space while the last 15 are administrative. Of the 12 that deal with space directly, I, II, VI, IX, and XII have potential ramifications on SRU including asteroid mining.

Article I sets the tone for the document by stating that the “*exploration and use of outer space [...] shall be carried out for the benefit and in the interests of all countries [...] and shall be the province of all mankind*” (United Nations Resolution 2222 (XXI) 1966). This passage illustrates the overarching intent of the Treaty; that outer space should be made, and remain, available to all parties equally.

Article II states that “*outer space, including the Moon and other celestial bodies, is not subject to national appropriation by claim of sovereignty, by means of use or occupation, or by any other means*” (United Nations Resolution 2222 (XXI) 1966). The word ‘national’ would suggest that appropriation of celestial bodies is only forbidden for governments; however, as noted in Article VI, States are responsible for all national activities in space, be they governmental or not. This article forms the basis of the argument against the legality of the acquisition and sale of space resources.

Article VI places international responsibility on States for national activities in space, be they governmental or non-governmental. States must authorize and continually supervise the activities of non-governmental entities in their jurisdiction (United Nations Resolution 2222 (XXI) 1966).

Article IX forbids cross-contamination of Earth and celestial bodies. While the introduction of processed asteroid materials to Earth are unlikely to cause the “adverse changes in the environment” that the article prohibits, certain extraction

techniques (e.g. biomining) could be deemed to contaminate the asteroid and, therefore, be impermissible according to this Article (United Nations Resolution 2222 (XXI) 1966).

Article XII states that stations, installations, vehicles, and equipment in space are to be made available on a reciprocal basis for visits from representatives of other States Parties to the Treaty (United Nations Resolution 2222 (XXI) 1966). A possible implication to the space mining industry is the inability to preserve the exclusive knowledge of novel technologies and methods.

The Moon Agreement

The *Agreement Governing the Activities of States on the Moon and Other Celestial Bodies* (Moon Agreement) entered into force on July 11, 1984 (COPUOS 2017b). The Moon Agreement directly addresses the exploitation of space resources, a unique feature among the five UN space treaties. It should be noted that for the purposes of this Agreement the term Moon refers to not only the Moon but also any celestial body within the solar system.

Article 6, paragraph 2 of the Agreement asserts that States Parties may collect and distribute samples of the Moon for scientific study (United Nations 1979). States Parties may also use appropriate quantities of space resources in support of their missions (ISRU).

Article 11, paragraph 3, reaffirms the prohibition of sovereign claims laid out in Article II of the OST by stating that “*neither the surface nor the subsurface of the Moon, nor any part thereof or natural resources in place, shall become property of any State, international intergovernmental or non-governmental organization, national organization or non-governmental entity or of any natural person*” (United Nations 1979). Paragraph 5 goes on to say that States Parties to the Agreement agree to form “*an international regime [...] to govern the exploitation of the natural resources of the Moon as such exploitation is about to become feasible*” (United Nations 1979). Paragraph 7(d) establishes “[a]n equitable sharing by all States Parties in the benefits derived from those resources” with special consideration for those directly or indirectly involved and to developing nations” (United Nations 1979).

The Moon Agreement thus prohibits the commercialization of space resources except by an international regime designed for the mutual benefit of all States Parties. Fortunately for private asteroid mining firms, the Agreement has only 17 members, none of which are major players in space exploration.

National Legislation

To date, two nations – the United States and Luxembourg – have passed legislation encouraging private sector involvement in space resource development by explicitly granting their citizens the legal right to own and sell space resources.

The United States

The United States Commercial Space Launch Competitiveness Act (CSLCA) came into force on November 25, 2015 (United States Commercial Space Launch Competitiveness Act of 2015). Title IV section 51303 states that it is legal for U.S. citizens to engage in the commercial exploration and recovery of

space resources. U.S. citizens are granted the right to “*possess, own, transport, use, and sell*” any obtained space resource in accordance with applicable law, including U.S. international obligations. By its citizens exercising this right the bill claims that U.S. is not asserting sovereignty or claiming ownership of any celestial object.

Luxembourg

In July 2017 the small country of Luxembourg became the first European nation to pass space resource legislation with the *Loi du 20 juillet 2017 sur l'exploration et l'utilisation des ressources de l'espace* (Law of 20 July 2017 on the exploration and use of space resources) (Government of Luxembourg 2017). Effective August 1, 2017, the bill grants similar rights as the United States' CSLCA but with the modification that these rights are available not only to citizens, but also to any corporation with an office in the country of Luxembourg. US firms Planetary Resources and Deep Space Industries (acquired by Bradford Space) both have offices in the country.

There is a lack of consensus in the space law community as to whether these Acts are in accordance with the OST. Under international law, property rights can only be attributed by a superior power (Tronchetti 2015). This power, the State, can only attribute property rights if the State itself has rights to the property first. In this sense, for State governments to grant space resource property rights to their citizens they are in effect appropriating the property rights for themselves first. This is in violation of Article II of the OST. Others argue that the OST does not expressly prohibit the commercialization of space resources and national legislation such as these are valid interpretations of the rights afforded to each State in accordance with Article VI of the same treaty.

CURRENT STATE OF THE ASTEROID MINING INDUSTRY

Thus far, Planetary Resources has launched and tested two versions of their Arkyd spacecraft; Arkyd-3 Reflight in 2015 and Arkyd-6 in 2018 (Planetary Resources 2017). Their first spacecraft to collect data from asteroids, Arkyd-301, is in development. The Arkyd-301 will be designed to be small and inexpensive enough to permit the simultaneous deployment of multiple identical spacecraft by a single launch vehicle, each destined for its own target asteroid (Planetary Resources 2018). Spacecraft miniaturization, a trend also evidenced by the recent popularity of CubeSats, is the key to deploying enough spacecraft to explore numerous NEAs in a timely and cost-effective manner. The Arkyd-301 will perform compositional surface mapping and will also include four on-board probes to directly sample the asteroid (Planetary Resources 2018). Data from the Arkyd-301 fleet will be used to select Planetary Resources' first mining target and inform the development of their mining architecture. Planetary Resources missed funding goals throughout 2018 and has been forced to downsize. On October 31, 2018, they were purchased by the blockchain company Consensus Systems Incorporated (ConsensusSys Inc.), leaving their future somewhat uncertain.

Until their purchase by Bradford Space in January 2019, Deep Space Industries had placed an emphasis on developing

propulsion technology, with two propulsion systems, Comet and Meteor, being available for purchase. Bradford Space have continued development of the Comet thruster (Bradford Space 2019a). They have also continued the development of the low-mass, low-cost prospecting Xplorer spacecraft, now renamed Explorer. This spacecraft will be capable of transporting a 10 kg payload from low Earth orbit to interplanetary space (Bradford Space 2019b).

Planetary Resources, Bradford Space, and TransAstra are not the only companies working towards making asteroid mining a reality. Luxembourg based Kleos Space S.à.r.l., a subsidiary of UK based Magna Parva Limited, is collaborating with the Luxembourg Institute of Science and Technology and has received funds from the Luxembourg Government to develop in-space manufacturing technology (LIST 2017). Aten Engineering (<https://www.atenengineering.com>), headquartered out of Portland, Oregon, is working towards making efficiencies in the domain of asteroid detection and characterization. OffWorld (<https://www.offworld.ai>) is a robotics company with branches in Pasadena, California and Luxembourg. Their long-term goals are to create autonomous industrial robots for use on Earth, the Moon, Mars, and asteroids.

PRIVATE-PUBLIC PARTNERSHIPS

Private-public partnerships (PPPs) are designed to split the cost, risk, and effort between government and industry. The private partner accepts more risk and responsibility versus a traditional arrangement, incentivizing increased efficiency. The Commercial Orbital Transportation Services (COTS) and Commercial Resupply Services (CRS) programs, initiated by NASA's Commercial Crew and Cargo Program Office in 2006 and 2008, culminated in the development and deployment of SpaceX's Dragon and Orbital Sciences Corporation's (now Orbital ATK) Cygnus, the first two private spacecraft to dock with and resupply the International Space Station (Hackler 2014).

The success of COTS has been described as a “new era in spaceflight” (Hackler 2014). A paper by Entrena Utrilla (2017) proposes the simultaneous and synergistic development of an asteroid resource utilization PPP dubbed Asteroid COTS. Given the recent success of PPPs enjoyed by NASA, and the potential gains the agency would see from advancement of commercial spacecraft and the installation of cis-lunar propellant depots, an asteroid resource PPP seems a likely possibility. NASA has awarded contracts to asteroid mining companies before; Deep Space Industries and Planetary Resources each received two contracts as part of the Asteroid Redirect Mission (Mahoney 2014).

OPPORTUNITIES FOR CANADA

Canada has a long and proud mining tradition (e.g. Cranstone 2002). This pillar of the economy is underpinned by mineral exploration and prospecting and there are more than 2000 Canadian mining and mineral exploration companies. These companies operate worldwide and account for nearly 37% of the budgeted global exploration expenditures. In 2016, Canada produced \$111B worth of minerals (including mineral fuels),

the sixth most of any nation (Reichl et al. 2018). Mining is Canada's third largest industry, worth 8.5% of its GDP in 2018 (Statistics Canada 2018). At the same time, Canada also has a distinguished and celebrated history of space robotics, most famously the Canadarm and Canadarm2, both built by MacDonald, Dettwiler and Associates (MDA), now part of Maxar Technologies Ltd. Canadian space companies are also well known for their expertise in the instrumentation needed for prospecting NEAs, for example, the OSIRIS-REx Laser Altimeter (OLA) instrument on the OSIRIS-REx spacecraft that is currently mapping asteroid Bennu (Daly et al. 2017).

It is also important to note that investment in technologies required for asteroid mining also stands to benefit mining on Earth through the development of spin off technologies. Indeed, interest in technology developments to aid mineral exploration and mining is growing. In an article in the *Globe and Mail* (March 30, 2014) entitled "*Innovation key to maintaining Canada's leader status*", Lee Hodgkinson wrote "*All Canadian resource industries will need to adopt an innovative approach through extensive research and development, use of technology, and promote an influx of new young talent.*" In a 2012 report entitled *100 Innovations in the Mining Industry*, the Ontario Mining Association noted several innovations in exploration, including lidar, portable spectrometers, and remote predictive mapping, all key strengths of the Canadian space community.

Considering the above, asteroid mining might seem like a natural fit for Canada; however, despite having the necessary expertise, the Canadian private sector is so far devoid of any companies working directly on asteroid mining. In addition, the government has not passed any space mining legislation and there is little indication on where they stand on the legality of SRU. However, a major step forward was the release of the Canada Mineral and Metals Plan (CMMP) in March 2019, which highlights SRU as a new frontier in mining for Canada; this plan also calls for the development of a policy approach for SRU in Canada (NRCan 2019). Only a few days before the release of the CMMP, the Prime Minister of Canada also announced that Canada is joining NASA on the Lunar Gateway initiative that will see humans return to the Moon. In summary, there is a significant opportunity for Canada to invest in SRU – for the Moon and Mars, as well as asteroids – given the current state of the mining and space exploration sectors in Canada.

THE FUTURE

Economic utilization of asteroid resources is not an impossible goal, but before the wealth of the solar system can be realized there are significant hurdles to overcome. Advances in spacecraft propulsion technology and robotic resource extraction autonomy will be required to process material at a sufficient scale to be economical. Before this stage, however, the catalogue of NEAs, with an emphasis on more accurate spectral data, must be expanded. The paucity of prospective asteroid mining targets (1 in 2300 for water) dictates that extensive ground-based observations must be made prior to the selection of asteroids to which prospecting spacecraft will be sent. New NEA discoveries should have their spectra immediately

characterized by follow up observations and efforts should be made to make spectral observations for as many known NEAs as possible. Since asteroid resources are likely to be acquired via appropriation of the resource only, and not of the host asteroid, the exclusive knowledge of prospective asteroids is extremely valuable, even before spacecraft visitation or the commencement of a mining operation.

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