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How many ore-bearing asteroids?

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ABSTRACT

A simple formalism is presented to assess how many asteroids contain ore, i.e., commercially profitable material, and not merely a high concentration of a resource. I apply this formalism to two resource cases: platinum group metals (PGMs) and water. Assuming for now that only Ni–Fe asteroids are of interest for PGMs, then 1% of NEOs are rich in PGMs. The dearth of ultra-low delta-v (<4.5 km s^{-1}) NEOs larger than 100 m diameter reduces the ore-bearing fraction to only ~1 in 2000 NEOs. As 100 m diameter NEOs are needed to have a value ≥US\$1B and the population of near-Earth objects (NEOs) larger than 100 m diameter is ~20,000 (Mainzer et al., 2011) the total population of PGM ore-bearing NEOs is roughly 10. I stress that this is a conservative and highly uncertain value. For example, an order of magnitude increase in PGM ore-bearing NEOs occurs if delta-v can be as large as 5.7 km s^{-1}. Water ore for utilization in space is likely to be found in ~1/1100 NEOs. NEOs as small as 18 m diameter can be water-ore-bodies because of the high richness of water (~20%) expected in ~25% of carbonaceous asteroids, bringing the number of water-ore-bearing NEOs to ~9000 out of the 10 million NEOs of this size. These small NEOs are, however, hard to find with present surveys. There will be ~18 water-ore-bearing NEOs >100 m diameter. These estimates are at present highly imprecise and sensitive to small changes, especially in the maximum delta-v allowed. Nonetheless the low values found here mean that much improved determinations of each of the terms of the formalism are urgently needed. If better estimates still find small numbers of ore-bearing NEOs then thorough surveys for NEA discovery and, especially, characterization are needed. Strategies for the two classes are likely to be different.

1. Introduction

For the mining of asteroids to become an engineering and commercial reality requires that we make a good assessment of how many asteroids contain ore. Here I use the term "ore" in the sense used in the terrestrial mining community, i.e., "*Ore is commercially profitable material*" (e.g., Sonter, 1997). Ore is not simply a high concentration of some resource, but includes consideration of the cost of extraction of the resource and its price. Hence we need to sieve the total asteroid population for the smaller populations that may be profitable to mine. Main belt asteroids are too hard to reach, so I will concentrate on the population of near-Earth objects (NEOs) which is overwhelmingly made up of asteroids, but with an admixture of comets. The NEO population is large. There are ~20,000 NEOs larger than 100 m diameter (Mainzer et al., 2011), and of order 10 million larger than 20 m diameter (Brown et al., 2013).

In this paper I introduce a simple formalism to evaluate how many ore-bearing asteroids are there. This formalism is likely to be reasonably robust. I then apply this formalism to two cases, the platinum group metals (PGMs) and water, using the limited available data. The values resulting from this analysis are by no means definitive, but the resulting values are quite small. The small numbers imply that further investigations to improve these estimates are urgent. Some possible paths forward are discussed for each term.

2. Quantifying the question

We can quantify the number of ore-bearing NEOs, $N_{\rm ore}$, for a given resource as the product of $P_{\rm ore}$, the probability that an NEO is ore-bearing, and $N(>M_{\rm min})$, the number of NEOs larger than a minimum profitable mass, $M_{\rm min}$, for that resource

$$N_{\rm ore} = P_{\rm ore} \times N(>M_{\rm min}) \tag{1}$$

$P_{\rm ore}$ is then the product of several factors[1]

$$P_{\rm ore} = P_{\rm type} \times P_{\rm rich} \times P_{\rm acc} \times P_{\rm eng} \tag{2}$$

here $P_{\rm type}$ is the probability that an asteroid is of the resource bearing type, $P_{\rm rich}$ is the probability that this type of asteroid is

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[1] This formalism is the same as that of the Drake equation for estimating the number of civilizations in the Galaxy capable of being detected (http://www.seti.org/drakeequation). Fortunately, the asteroid case has two fewer terms and better determined values.

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sufficiently rich in the resource. The product of P_{type} and P_{rich} determines the fraction of NEOs with a high concentration.

In addition to a high resource concentration, C_r, qualifying an NEA as ore-bearing requires economical extraction of the resource, including its return to a location where it can be sold. I use two terms to quantify this challenge. P_{acc} is the probability that the asteroid is in an accessible orbit and is discussed in Section 3. P_{eng} is the probability that the resource can be extracted profitably, as discussed in Section 6. Other factors can be added to these equations as the calculations become more refined, but these capture the essence of the problem.

$N(>M_{min})$ depends the retrievable ore value in the asteroid, $\Lambda_{ore}=\varepsilon M C_r \lambda$, where ε is the resource extraction efficiency which will likely be substantially less the unity, at least initially (Kargel, 1994), and where λ is the price/kg of the resource at the point where it can be sold, either on Earth or at various locations in space (see Section 5). The total revenue must yield an acceptable profit given the substantial risk and long timescale of asteroid mining ventures.

Asteroid masses are hard to determine without sending a spacecraft close to the NEO. Only one mission, Hayabusa, has gone to a sub-km-sized NEO (Fujiwara et al., 2006). A minority of NEOs are binaries. For these, and for those undergoing close flybys of other massive bodies, Kepler's third law allows a mass to be derived (Merline et al., 2002). Radar can determine masses for NEOs passing close to Earth (≤ 0.1 AU, Ostro et al., 2002,[2]). But for the majority of NEOs a mass must be inferred from an assumed mean density and a diameter, so we must use a minimum diameter, D_{min}, as a proxy for M_{min}.

The resource extraction process includes a myriad of engineering details, which I subsume into P_{eng}. Evaluating P_{eng} is too complex to include in this paper (see the discussions in Kargel (1994) and Lewis et al. (1993). Hence I will take $P_{eng}=1$ throughout, so that all estimates of N_{ore} given in this paper should be taken as upper limits. Some issues related to P_{eng} are discussed in Section 6, including the possible dependence of the other terms on P_{eng}, which would spoil the simple factorization of Eqs. (1) and (2) by adding joint probabilities.

The numbers needed to evaluate Eqs. (1) and (2) are at present mostly not well determined. Here I collect the available data in order to make an initial estimate of P_{ore} and N_{ore} for two much discussed cases – platinum group metals (PGMs) and water. The results are instructive. In the discussion I consider how to improve these estimates, how to increase N_{ore}, and how to find the ore-bearing NEOs.

3. Accessibility

Accessibility is primarily determined by the energy needed to go out to the asteroid with the mining equipment and to return with the ore. This energy is conventionally measured by delta-v, the change in velocity needed to transfer between orbits. The minimum energy trajectory is called a Hohmann transfer orbit (Hohmann, 1960). The outbound delta-v can be approximated using the Shoemaker and Helin (1978) formalism. The return delta-v is more important than the outbound delta-v because a much larger mass of ore needs to be returned than the mass of the mining equipment sent out. Small changes in delta-v make for large differences in the mass that can reach an NEO (Elvis et al., 2011).

Benner has computed the outbound Hohmann delta-v values for all known NEOs from low Earth orbit (LEO) to an asteroid rendezvous orbit.[3] Values range for 3.8–28.0 km s^{-1}, with a median of 6.65 km s^{-1} (Fig. 1, Elvis et al., 2011). Given the large payloads that mining missions, or a human expedition, would require, a lower delta-v is needed. Elvis et al. (2011) show that choosing an NEO with delta-v=4.5 km s^{-1} can double, or even quadruple, the payload delivered to the NEO compared with the median. This value includes only a small fraction of all known NEOs (Fig. 1, black line).

The orbital dynamics that scatters asteroids into NEO orbits has no dependence on mass (Bottke et al., 2002), hence it is expected that size and orbit parameters are uncorrelated in the full NEO population. However, present surveys for NEOs are incomplete. In the 100–300 m size range (roughly an absolute magnitude,[4] $H\sim 22$) over 80% of NEOs remain undiscovered (Mainzer et al., 2011). The larger known NEOs with $H<22$ have a higher median delta-v (8 km s^{-1}) than the smaller ($H>22$) known NEO population (6.4 km s^{-1}). This is a selection effect in the known population as smaller NEOs can only be found when they are closer and so are more easily found if they have relatively Earth-like orbits.

For the $H>22$ NEOs delta-v=4.5 km s^{-1} corresponds to $P_{acc}=2.5\%$ (Fig. 1, blue line). To reach $P_{acc}=25\%$ requires only delta-v=5.7 km s^{-1}, so P_{acc} is highly sensitive to the choice of delta-v cut. Very small NEOs (24–60 m, $25<H<27$, Fig. 1, green line) have a similar distribution to all $H>22$ objects at low delta-v. Larger NEOs (diameter >100 m, $H<22$) have $P_{acc}=0.1\%$ at delta-v=4.5 km s^{-1} and reach $P_{acc}=10\%$ only at delta-v=6.2 km s^{-1} (Fig. 1, black line). As larger NEOs are more easily found their distribution should be more representative of the full NEO population. Both improved modeling of the NEO population (e.g., Greenstreet and Gladman, 2012) and more complete observations can clearly have a big effect on our assessment of P_{acc}.

4. Platinum group metals

First I consider the platinum group metals (PGMs): platinum (Pt), rhodium (Rh), osmium (Os), iridium (Ir), palladium (Pd), and rhenium (Re). These elements are rare in the Earth's crust as they are siderophiles – i.e., they dissolve readily in molten iron – and so are mostly trapped in the Earth's core. As a result, several researchers (e.g., Kargel, 1994) have identified the PGMs as the most promising asteroidal ore, because of their high value on Earth (~US\$50k/kg, approximate present Pt prices).[5] Selling asteroid-derived resources on Earth has the advantage of not needing the development of a market for the resource in space.

Kargel (1994) discusses the fraction of NEOs that might be rich in PGMs, P_{type}, in Eq. (1). The answer is not simple, as the choice of asteroid type depends on the ore extraction method. The richest asteroids would be M-type, which are thought to be those that deliver PGM-rich nickel–iron (Ni–Fe) meteorites to Earth, a subset of the X-class asteroids. I will concentrate on these, realizing that improved estimates for other PGM-rich asteroids need to be developed.

Binzel et al. (2004) compiled statistics for both (Bus et al. (2004) and Tholen (1984) classifications of NEOs. They find only three M-type NEOs. However, in addition, 27% of the 47 X-class asteroids, which have rather ambiguous spectra, will turn out to be M-type, if the ratios of E, P, and M types that make up the X-class remain the same (4, 4, 3, respectively). Adding these expected M-types gives a total of 16 out of a sample of 376. Hence $P_{type}\sim 4\%$.

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[2] See also the plots at http://echo.jpl.nasa.gov/~lance/snr/far_asnr18.gif.

[3] http://echo.jpl.nasa.gov/~lance/delta_v/delta_v.rendezvous.html.

[4] An asteroid's absolute magnitude H is the visual magnitude an observer would record if the asteroid were placed 1 Astronomical Unit (AU) away, and 1 AU from the Sun and at a zero phase angle (http://neo.jpl.nasa.gov/glossary/h.html). Conversion from H to an approximate diameter is given at http://neo.jpl.nasa.gov/glossary/h.html. $H=22$ corresponds to a diameter between 110 m and 240 m for typical albedos.

[5] http://www.platinum.matthey.com