HOW MANY ORE-BEARING ASTEROIDS? M. Elvis,
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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. “Ore” has a technical meaning in the terrestrial mining community: “Ore is commercially profitable material” [1]. I.e. ore is not simply a high resource concentration, but includes consideration of the cost of extracting the resource and its price. Hence we need to sieve the total asteroid population for the smaller populations that may be profitable to mine.

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 [2]. I apply this formalism to two resource cases: platinum group metals (PGMs) and water.

Re-applying the Drake Equation Formalism: We can quantify the number of ore-bearing NEOs, Nore, for a given resource as the product of Pore, the probability that an NEO is ore-bearing, and N(Mmin), the number of NEOs larger than a minimum profitable mass, Mmin, for that resource:

\[ N_{\text{ore}} = P_{\text{ore}} \times N(>\text{M}_{\text{min}}) \]

Pore is then the product of several factors:

\[ P_{\text{ore}} = P_{\text{type}} \times P_{\text{rich}} \times P_{\text{acc}} \times P_{\text{eng}} \]

This formalism is the same as that of the Drake equation for estimating the number of civilizations in the Galaxy capable of being detected [1]. Fortunately, the asteroid case has two fewer terms and much better determined values.

Ptype is the probability that an asteroid is of the resource bearing type, P rich is the probability that this type of asteroid is sufficiently rich in the resource. The product of Ptype and P rich determines the fraction of NEOs with a high concentration.

In addition to a high resource concentration, C, 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. Parec is the probability that the asteroid is in an accessible orbit. P eng is the probability that the resource can be extracted profitably.

\[ N(>\text{M}_{\text{min}}) \] depends the retrievable ore value in the asteroid, \( A_{\text{ore}} = \epsilon M C r \lambda \), where \( \epsilon \) is the resource extraction efficiency, and \( \lambda \) is the price/kg of the resource at the point where it can be sold, either on Earth or at various locations in space. The total revenue must yield an acceptable profit given the substantial risk and long timescale of asteroid mining ventures.

The resource extraction process includes a myriad of engineering details, which I subsume into P eng. I will take P eng = 1 throughout, so that all estimates of Nore given in this paper should be taken as upper limits.

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.

An NEO with delta-v = 4.5 km s\(^{-1}\) can double or quadruple the payload delivered to the NEO compared with the median [3]. For H > 22 NEOs delta-v = 4.5 km s\(^{-1}\) corresponds to Parec = 2.5% (Figure 1, blue line). To reach Parec = 25% requires only delta-v = 5.7 km s\(^{-1}\), so Parec is highly sensitive to the choice of delta-v cut.

Platinum Group Metals (PGMs): Concentrating on Ni-Fe asteroids, Binzel et al. [4] find only 3/376 M-type NEOs. Another ~16 of the X-types will be M-type leading to P type ~ 4%. (Pallasites add negligibly to the population.) For Ni-Fe meteorites Ir concentrations span four orders of magnitude, from 0.01 to 100 parts per million (ppm). Figure 2 shows the Ir concentration distribution [5] a proxy for all PGMs which in total have ~7 times this C. Half have C above that of terrestrial mines, a minimum threshold. So P rich = 0.5.

Combining these estimates gives:

\[ P_{\text{ore}}(\text{PGM}) = P_{\text{type}} \times P_{\text{rich}} \times P_{\text{acc}}(4.5\text{km s}^{-1}) \]

\[ = 0.04 \times 0.5 \times 0.025 \]

\[ = 5.0 \times 10^{-4}. \]

That is 1/2000 of the total NEO population.

1 http://www.seti.org/drakeequation
The number of PGM ore-bearing NEOs depends on how many with high Cr are large enough to plausibly return a profit. Rather arbitrarily I take \( \Lambda_{\text{ore}} = \$11B \) as a threshold. This determines \( M_{\text{min}} \), the minimum mass NEO worth mining for PGMs and, given a density, the minimum diameter, \( D_{\text{min}} \). For a reasonable density of 4500 kg m\(^{-3}\), \( D_{\text{min}} = 100\) m. There are a total of \( \sim20,000 \) NEOs this size or larger.

Combining these estimates the total number of PGM ore-bearing asteroids, \( N_{\text{ore}}(\text{PGM}) \), is likely to be about 10. I stress that this number has large uncertainties and includes only metallic asteroids. Nonetheless, the number is surely smaller than would-be asteroid miners may have expected.

**Water:** To mine water the carbonaceous (C-type) asteroids are the target. C-types comprise (9.8±3.3)% of the NEO population [7]. Hence \( P_{\text{type}} = 0.1 \) is reasonable. Asteroidal water is either bound up in hydrated minerals such as clays, or may be present as ice distributed among the rock. The amount of ice in an NEO would depend on the porosity. Meteoritic microporosities are 1% to \( \sim20\% \) [8]; macroporosities are measured only approximately for just three C-type NEOs [6] at 28%, 39% and 60%.

The 20,000 times higher C\(_r\) for water-rich NEOs compared with PGM-rich NEOs opens up the much more numerous population of smaller NEOs, even for delivery to LEO. To reach \( \Lambda_{\text{ore}} = \$1.18B \), as used for PGMs, with a \( C_{\text{r}}(\text{water}) = 20\% \) requires only the water from an 18 m diameter carbonaceous NEO delivered to LEO and sold at \$5 k kg\(^{-1}\). A recent redetermination of the number of 20 m class impacts on the Earth’s atmosphere, calibrated using the Chelyabinsk event, has increased the estimate of the number 20 m or larger NEO by a factor \( \sim10 \) to about \( \sim10 \) million [8], so the total population of water-ore-bearing NEOs, \( N_{\text{ore}}(\text{water}) \sim9000 \).

NEOs of this smaller size are hard to discover and characterize. The absolute magnitude of an 18 m diameter carbonaceous asteroid is \( H = 27 \), detectable only within \( \sim15 \) lunar distances. If instead we use the number of the more readily found \( H < 22 \) NEOs then the steep frequency-size curve for NEOs in this size range gives \( N(>D_{\text{min}}) = 20,000 \), as for the PGM case, and \( N_{\text{ore}}(\text{water}) \sim18 \).

**Conclusions:** The most important conclusion of this study is that this formalism exposes the key factors for asteroids to be ore-bearing, and that examining them shows that all the values for \( P_{\text{type}}, P_{\text{rich}}, P_{\text{acc}} \) and \( N(>M_{\text{min}}) \) used to make this assessment are in need of far better definition.

The apparently limited supply of potentially profitable NEOs argues strongly for an accelerated rate both for discovery and especially for characterization, which is lagging badly behind discovery.

As good targets appear to be scarce, the knowledge of which NEOs are ore-bearing could itself become commercially valuable intellectual property.

**References:**