HOW MANY ORE-BEARING ASTEROIDS? M. Elvis[1], [1]Harvard-Smithsonian Center for Astrophysics (60 Garden St. Cambridge MA 02138 USA).

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

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

P_{ore} is then the product of several factors:

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

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.

P_{type} 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 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. P_{eng} is the probability that the resource can be extracted profitably.

$N(>M_{min})$ depends the retrievable ore value in the asteroid, $\Lambda_{ore} = \varepsilon M C_r \lambda$, where ε is the resource extraction efficiency, and 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. 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 N_{ore} 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.

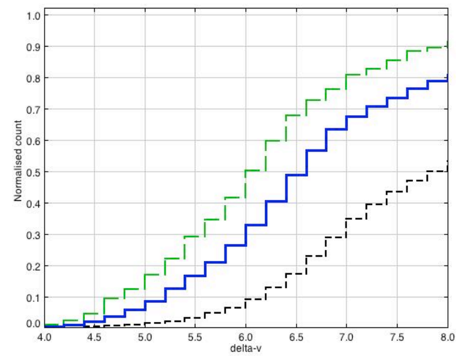

Figure 1: Cumulative outbound delta-v for NEOs [http://echo.jpl.nasa.gov/~lance/delta_v/delta_v.rendezvous.html]. Black: NEOs with H < 22 (diameters < 100 m); blue: NEOs with H > 22 (dia. >100 m); curve: NEOs with 25 < H < 27 (dia. 24 – 60 m, for low, 0.05, albedo objects).

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 P_{acc} = 2.5% (Figure 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.

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 negligably 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_r. Half have C_r above that of terrestrial mines, a minimum threshold. So P_{rich} = 0.5.

Combining these estimates gives:

$$P_{ore}(PGM) = P_{type} \times P_{rich} \times P_{acc}(4.5 \text{km s}^{-1}) = 0.04 \times 0.5 \times 0.025 = 5.0 \times 10^{-4}.$$

That is 1/2000 of the total NEO population.

[1] http://www.seti.org/drakeequation

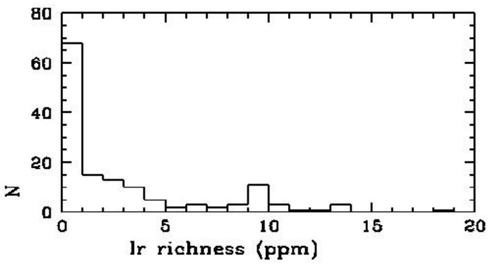

Figure 2: Meteoritic Ir richness distribution [5].

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 Λ_{ore} = US\$1B as a threshold. This determines M_{min}, the minimum mass NEO worth mining for PGMs and, given a density, the minimum diameter, D_{min}. For a reasonable density of 4500 kg m-3 [6], Dmin = 100 m. There are a total of ~20,000 NEOs this size or larger.

Combining these estimates the total number of PGM ore-bearing asteroids, N_{ore}(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_{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 ~20% [8]; macroporosities are measured only approximately for just three C-type NEOs [6] at 28%, 39% and 60%.

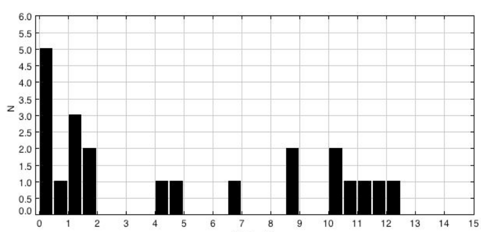

Figure 3: Meteoritic H_2O wt% distribution [9].

The fraction of water bound into silicate clays is better measured (Figure 2). 31% (6/19) is the best estimate of the high water concentration group C_r(ice). I take P_{rich} =0.25. For smaller (H > 22) NEOs P_{acc} = 3%, for delta-v < 45 km s^{-1}. Hence the probability of a NEO being water-ore-bearing (table 2) is:

$$P_{ore}(\text{water}) = P_{type} \times P_{rich} \times P_{acc}$$
$$= 0.1 \times 0.31 \times 0.03$$
$$= 9 \times 10^{-4}$$

I.e. roughly 1/1100 NEOs are water-ore-bearing, quite comparable to PGM ore-bearing asteroids.

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 Λ_{ore} = US\$1.18 B, as used for PGMs, with a C_r(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 ~10 to about ~10 million [8], so the total population of water-ore-bearing NEOs, N_{ore}(water) ~9000.

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 ~15 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 $N(>D_{min})$ = 20,000, as for the PGM case, and N_{ore}(water) ~ 18.

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_{type}, P_{rich}, P_{acc} and $N(>M_{min})$ 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:

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