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# Astronomical Prospecting of Asteroid Resources

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## Abstract

Ore-bearing asteroids are not common among the known population. As a result, asteroid resource extraction requires that large numbers of asteroids be classified by their composition, and have precise orbits known. At present only near-Earth asteroids (NEAs) are accessible with massive (≥5mt) equipment that is likely needed for mining. Of the ~15,000 known NEAs, no more than 2000 have a taxonomic type. NEA discoveries are growing by ~2000/year, with most new discoveries being faint (V~20-21 at discovery). We have begun a program with the 6.5 m Magellan telescope and the PISCO 4-color imager to obtain precise colors and tracks for faint NEAs. This program can be scaled to characterize all NEAs as they are discovered. This "astronomical prospecting" can help close the business case for asteroid mining companies.

## 1. Introduction

Asteroids number in the millions and the total mass of industrially useful raw materials they contain is far vaster than the accessible materials in the Earth's crust [6]. This abundance has drawn great attention lately with a number of commercial companies developing ways to prospect for the most promising asteroids.

The mining industry term for commercially profitable concentrations of materials is *ore-bearing*. A rich vein of the desired material is not enough. A profit is essential. Ore-bearing is a technology dependent term. Improved methods can change material into being ore-bearing. It is also economics dependent, as a drop in price can render material non-ore-bearing, and vice versa.

There are a series of physical factors that reduce the number of asteroids that could be profitable to mine with current technology [3]. In total there remain many potentially ore-bearing asteroids, but as a fraction of the total among known NEAs they are quite rare, roughly 1 in 660, or 1 in 66 if low delta-v asteroids are preselected.

This fraction could rise if a thermal infrared survey of NEAs were undertaken, as the optically dark carbonaceous asteroids may well be far more common in such a survey [7]. Until at least the mid-2020s though we have only NEAs selected by their reflected optical light.

If a low delta-v NEA is selected at random some 100 must be visited to find one ore-bearing asteroid. Instead, if a rough classification into one of the 3 main type: stony (S), carbonaceous (C) or uncertain, and possibly metallic (X), then this number can be reduced to about 10 [4]. Cutting the number of spacecraft probes by an order-of-magnitude may be enabling for the closing of the business case.

Unfortunately, current investigations of NEAs, while highly successful at discovery, fall behind on the information gathering needed for prospecting [1]. Of the 2000 or so NEAs being discovered each year, almost half have ill-determined orbits in the sense that they will be almost impossible to re-acquire at their next close approach ("apparition"). An even greater fraction, ~90%, have no spectral information, and so have undetermined types.

Here we show that high quality optical imaging in 4 colors obtained from ground-based telescopes provide the most efficient method for obtaining the necessary orbit and type information that is basic to asteroid prospecting. To obtain this data needs large (>6m) telescopes with custom-built instrumentation and professional astronomers. We describe our pilot program at the 6.5m Magellan telescope in Chile using the PISCO 4-band imager.

## 2. Optical Colors and Astrometry

The standard method for obtaining asteroid types is to use near-infrared spectroscopy. However, the strong sky background in this band [2] sets a limit at V~19. As most new NEAs are discovered 1-2 magnitudes fainter, and then fade quite rapidly [1], a more sensitive method is needed if most NEAs need to be characterized.

The sky background in the optical band is much fainter, so that V=21-22 objects are quite accessible. However, NEAs are fast-moving, so spectral information must be collected rapidly, and this demands the use of large telescopes, with ≥6m diameter primary mirrors. Observing time on these large telescopes is currently scarce.

With measurements at ≤1% accuracy, just 4 of the optical bands of the Sloan Digital Sky Survey (SDSS) - g,r,i,z - are sufficient to make a reliable basic typing of asteroids (S,C,X) [5].

For orbit determination, accurate position determinations on the sky ("astrometry") are essential over as long an arc of the asteroid's orbit as possible [1]. Ground-based telescopes have image sizes ~0.5 arcsec due to the unstable atmosphere ("seeing"). Centroiding allows Pan-STARRS to obtain positions good to ~0.1 arcsec. However, with signal-to-noise of 100 it is possible to centroid an asteroid position to 1%, i.e. ~10 milli-arcsec (mas).

Until this year that accuracy was not useful, as the reference frame of stars was not defined to that level of accuracy for a dense enough grid of stars that any image would contain a sufficient number of them. With the release of the first *Gaia* catalog [Gaia2017] this is changed. We will report on our study of how well this newly accurate astrometry can improve orbit determination for NEAs.

To take advantage of the accurate color and astrometric information now obtainable for NEAs requires an instrument carefully designed to give this information. The Parallel Imager for Southern Cosmology Observation (PISCO, [8]) is a photometric camera that comprises four focal planes with a common shutter, capable of obtaining *simultaneous* images over a 9 arcminute field of view in the SDSS g, r, i and z optical passbands. PISCO is installed on the Magellan Clay telescope and is used for many astrophysics research projects. Simultaneous multi-band imaging removes uncertainties due to asteroid rotation. The large field enables accurate photometry by main sequence fitting, and accurate astrometry using ≥10 Gaia stars.

We report on our pilot project to test and optimize the abilities of PISCO/Magellan to produce the asteroid prospecting data needed for asteroid mining to be profitable.

## 3. Summary and Conclusions

Considerations of the rarity of ore-bearing near-Earth asteroids among the known population and the extreme faintness of the majority of newly discovered near-Earth asteroids, require the use of large aperture (>6 m) optical ground-based telescopes for the accurate determination of their orbits and a preliminary determination of their composition. This information can greatly reduce the need for in situ prospecting and so close the case for asteroid mining.

The 1% accuracy of the measurements requires: (1) high signal-to-noise in short observations, hence large apertures; (2) specialized instrumentation, such as PISCO; (3) professionally trained astronomers.

Our pilot program on Magellan will be used to validate and optimize this astronomical prospecting.

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