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Exploiting Solar System Resources: Opportunities and Issues

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Asteroid Research

Asteroids are small rocky bodies (generally less than 100 km diameter, most of them smaller than 10 km) orbiting the Sun often in orbits between Mars and Jupiter, a region known as the Asteroid Belt. They are considered the fragments of the original material which made up the solid parts of the planets in our solar system.

There exist three motivations for wishing to understand the structure of asteroids. The main motivation behind our work at the Vatican Observatory is to understand the formation of the planets, 4.6 billion years ago. For example, we have reason to believe that meteorites, which have radioactive closure ages of about 4.6 billion years, represent samples of those asteroids and thus their study can give us clues to the evolutionary history of the solar system itself.

There is another motivation for understanding the physical nature of the asteroids today, however. We now recognize that some asteroids do on occasion become perturbed into Earth crossing orbits, and some small fraction of those could potentially represent a threat to Earth's inhabitants. These events are not limited to the sorts of impact events like that which is thought to have triggered the mass extinctions of the K-T event 65 million years ago. Our best estimates now suggest that such enormous impacts are a once in a hundred million years event. But smaller, more common events can also have important effects on terrestrial life.

When the meteorite that formed Meteor Crater in Arizona hit, only 50,000 years ago, its impact was equivalent to a 10 megaton nuclear explosive. The force of the winds produced by the shock would have produced hurricane-level devastation in an area up to 40 of kilometers away from the impact site.

An impact like that is still relatively rare, but even smaller impacts could still have serious local effects. On 15 February 2013, the 30 m diameter asteroid 2012 DA14 (30 m) passed closer to Earth than the orbital altitude of geosynchonous satellites. On the same day, a completely unrelated 18 m fragment hit the Earth's atmosphere and exploded over the Russian city of Chelyabinsk; more than one thousand people were treated for injuries, mostly from flying glass as the sonic boom of the impactor shattered windows across this city of more than 1,000,000 inhabitants. It is estimated that objects similar to the Chelyabinsk impactor (fragments of which have been recovered, and shown to be made of ordinary chondrite material) probably hit the Earth at least once a decade.

There is a third motivation for studying asteroid composition and structure, however, which ties directly to the theme of Science and Sustainability. Within the next few decades these asteroids may well become new sources of natural resources. In fact, several asteroid mining companies are already set up and running, and NASA is actively working on the basic engineering of Space Mining. The exploitation of these resources presents both opportunities and cautions of which society should be aware.

The Meteorite-Asteroid Connection

One unique aspect of asteroid science is the recognition that we have in fact thousands of physical samples of the asteroids in our terrestrial meteorite collections, available for chemical and physical studies. From such measurements we can actually make specific claims about the composition and physical structure of asteroids.

There are many different lines of evidence supporting the meteorite-asteroid connection.

Some two dozen fireballs have been imaged from multiple locations with enough detail to allow one to trace their orbits, which have dropped meteorites onto the surface of the Earth that have been collected and shown to be typical meteorites. In every case, the observed orbits of the fireballs trace back to the asteroid belt.

Another strong line of evidence is to compare the observed spectra of the asteroids, especially in the near infrared where certain minerals produce diagnostic broad band features. These features in many asteroids

match the features in both wavelength and shape of features measured for ordinary chondrite meteorites in the lab.

The most telling evidence, of course, comes from returned samples. The Japanese Hayabusa mission to the small asteroid Itokawa brought back particles of dust whose chemical compositions exactly matches samples of the a particular ordinary chondrite subgroup, the LL group. Other sample return missions, including the NASA OSIRIS-REx mission and the JAXA Hayabusa II missions, are already launched and en route to their respective asteroid targets.

Just as the most common stony meteorites can be classified generally into two main groups, ordinary and carbonaceous, the most common asteroids likewise can be sorted into two main groups, “S” and “C”, based on their colors and brightness. Where Hayabusa visited an S asteroid, the two missions currently en route are both targeted to the as-yet-unsampled C type asteroids. By the early 2020s we will have solid data to connect these different asteroid spectra types with the different classes of meteorites (there do exist a relatively rare class of E-type asteroids which are though to be the source of enstatite chondrites, but this connection has yet to be confirmed).

Meteoritics at the Specola Vaticana

The primary research in meteoritics at the Vatican Observatory is measuring the physical properties of meteorites… their density, porosity, magnetic properties, and thermal properties. It is work that I began in collaboration with Prof. Daniel Britt at the University of Central Florida back in 1996, and it is being carried forward now at the Observatory, with Dr. Britt and other collaborators as part of a NASA funded Center for Lunar and Asteroid Surface Studies, with the active participation of our current curator of meteorites, Br. Robert Macke SJ. Several dozen refereed papers and research presentations have resulted from this work, which have been summarized in two review papers in the journal *Chemie der Erde.* ***[1]***

The Vatican meteorite collection is ideal for such survey work. The bulk of the collection consists of more than a thousand samples representing nearly every meteorite type from the comprehensive collection of the Marquis de Mauroy, donated to the Vatican by his widow in 1935.

Meteorites come in many different chemical and physical varieties, which has provided both challenges and opportunities for our work. However, for the purposes of the discussion in this paper, we can summarize the general groupings in this way.

About 85% of the meteorites that are seen to fall to Earth belong to a class called *Ordinary Chondrites*. The relative abundances of the chemical elements in these rocks closely parallels that seen in the atmosphere of the Sun itself, and they are thought to represent material similar to what made up the bulk Earth and other terrestrial planets. These elements are present as a mixtures of basic rock-forming elements, such as olivine, pyroxene, and plagioclase, which are found in small (less than a millimeter) beads called “chondrules”, held in a matrix of well-compressed fine grains. The matrix generally has the same composition as the chondrules, but in addition one finds distributed through the matrix many sub-millimeter flakes of iron-nickel metal, which contain as well the other metallic elements such as platinum and gold also present in the same relative abundances as seen in the Sun.

The next most common meteorite class are meteorites which are far more oxidized than the ordinary chondrites and with other distinctive chemical trends. They are known as *Carbonaceous Chondrites*. They make up about 8% of observed meteorite falls.

The name “carbonaceous” for this group can be misleading. While there are some meteorites within this group that contain up to 20% bound water and 5% or more carbon-bearing organic material, giving the group its name “carbonaceous”, there are many other meteorites now classified with these meteorites but which have essentially no carbon or water. More challenging, both the volatile-rich and volatile-poor members of this class tend to be very dark, which tends to suppress those spectral features in the visible or near infrared that would help distinguish one type from another either. Thus it is not easy to determine by remote sensing whether a given black rock is a volatile rich CI meteorite, a volatile poor CV meteorite… or an ordinary chondrite that has been turned black by shock.

The final chondrite class, the *Enstatite Chondrites*, make up 5% of observed falls. They are chemically the opposite of the carbonaceous meteorites, being chemically highly reduced but 20% to 25% by mass iron-nickel metal. They also contain interesting but at times exotic minerals rich in chromium, manganese, and titanium.

The other 9% of the meteorites seen to fall to Earth consist of a wide range of scientifically fascinating materials, whose study can provide great clues to the processes that occurred when our solar system was forming. For the purposes of the discussion below, however, it is sufficient to note that they are all quite rare. In particular, though the meteorites seen in museums often tend to be large pieces of metal, know collectively as *Irons*, such

meteorites are actually rarely seen to fall. Their dominance in our collections is the result purely of the fact that they are very easy to identify even by the casual observer when found among terrestrial rocks; and, unlike the ordinary chondrites, they can survive weathering in the water- and oxygen-rich atmosphere of Earth (typically, an ordinary chondrite is rusted into dust within a hundred years of sitting on the Earth's surface, except in dry places like the Sahara or Antarctica. By contrast, iron meteorites can survive on Earth for thousands of years).

This classification of meteorites by chemical type is the fruit of a century's worth of painstaking work in collections around the world. The bulk of the laboratory analysis done on meteorites today carries this work forward by using a variety of high-tech analytical devices to determine the precise compositions and isotopic characteristics of ever-smaller samples, in order to put ever tighter constraints on the chemical evolution of these samples.

However, as such work (strongly fueled by the need to analyze lunar samples from the Apollo era) was progressing in the latter half of the 20th century, the measurements of the physical properties of meteorites had not kept pace with our growing knowledge of meteorite chemistry. With that in mind, starting about 25 years ago, certain laboratories in Finland, Canada, Japan, and our group at the Vatican began the systematic measurement of meteorite physical properties: density, porosity, magnetic susceptibility, heat capacity, thermal and electrical conductivity, and strength under compression and extension. Knowing these properties is essential for understanding the physical evolution of the planets, and the planetoids from which they were formed. But, as we will see, it also has given us a tool for a completely different sort of endeavor.

The first stage of our work at the Vatican in measuring physical properties has been to determine the average bulk and grain densities of meteorite groups. These measurements, now essentially complete, are based on a survey of more than a thousand meteorites not only in our collection but samples obtained by taking our measurement equipment to collections around the world.

We found that bulk densities (where the volume of internal voids is included in the calculation of density) of most ordinary chondrite meteorites range from 2.8 to 3.6 g/cm3. The bulk of these samples have relatively low porosity, under 10%, which generally can be accounted for by the shock-induced microcracks imposed on the matrix of the sample long after its formation. By contrast, many carbonaceous chondrite meteorites turn out to be more porous than the ordinary chondrites, with the result that they have lower bulk densities. In particular, those carbonaceous meteorite types that are rich in organic materials and hydrated minerals (with OH or actual water present), the CI and CM groups, have much lower densities. For the most water rich meteorites, the bulk density is in the range of 2 to 2.5 g/cm3; the lowest bulk densities, for the two most water rich meteorites, are 1.6 g/cm3 reflecting not only the large amount of OH present but also their intrinsic high (up to 30%) porosities.

Asteroid Physical Properties

Whereas spectra only characterizes the surface layers of an asteroid, bulk physical properties such as density allow us to examine the content of the entire asteroid. Given this connection between meteorites and asteroids, it thus is interesting to compare the physical properties of the meteorites that we have measured with those properties of the asteroids themselves. In particular, the comparison between the densities of the meteorites we have measured with the densities of the asteroids where they are thought to be derived is of particular interest, and provides several important constraints on our understanding of how we might exploit those asteroids for their natural resources. Over the past twenty years, asteroid densities have been derived by a number of different techniques.

The average dimensions of an asteroid can be determined from ground-based observations in a number of ways. The observed brightness of an asteroid depends on three factors. Given that one is measuring the intensity of sunlight reflected from the asteroid, the amount of light we observe is in part determined by the distances of the asteroid from the Sun (and from us). The location of the asteroid is easily determined by knowing the rate of its orbit, using Kepler's Laws. A second factor is the intrinsic reflectivity of the material on the asteroid's surface, its *albedo.* For a given solar distance, a darker surface will absorb more sunlight than a brighter surface; thus, if its temperature can be determined by the observing in the infrared the shape and position of its black body radiation, one can then deduce its average albedo. Finally, the amount of visible light reflected from an asteroid surface depends on both its albedo and its size; and so, given the albedo determined from infrared observations, the size of the asteroid can then be calculated. Such measurements are nowadays typically quoted to a value of plus or minus ten percent.

Size is one essential factor in determining an asteroid's density; mass is the other essential factor. It is in fact a distinct challenge to be able to determine the mass of an asteroid; this can be done only by determining how the asteroid affects the orbits of some other object. With the advent of spacecraft missions into the asteroid belt, we can use the measured deflection of any spacecraft that passes close to an asteroid (or even better, by measuring the orbit of such a spacecraft about that asteroid) to derive very precise mass measurements. In

addition, however, over the past twenty years improvements in ground based telescopes using adaptive optics have allow us to detect natural moonlets in orbit around many dozens of asteroids; their orbits likewise allow one to determine the masses of the asteroids.

Only a few dozen asteroids in total have had both mass and size measured, to date, but the results of these measurements are quite startling: the observed asteroid densities range from 1.3 g/cm3 to 2.8 g/cm3 with the C type asteroids systematically less dense than the S types. In other words, the densities of asteroids appear in general to range from 25% to 50% less dense than the meteoritic material from which they are made. The inference is that asteroids today are not solid bodies, but rather loose piles of rubble.

This conclusion leads to the realization that the asteroids must have had a very complex evolutionary history. At the very least, the dust in the original solar nebula from which all solid bodies are derived must first have experienced an environment where it could be compacted into solid rocky material with low porosity, as seen today in most meteorites, while being accreted into large coherent bodies that then were catastrophically disrupted and re-accreted. How many times has this catastrophic disruption taken place? What is the relative time scale of the lithification versus accretion? What limits can we place on the times when each of these events occurred? The answers to all these questions will give us some fundamental markers as to what occurred at the same time that the larger planets, including Earth, were forming.

Asteroids, Resources, and Issues in Sustainability

About half a million asteroids have already been discovered, most of them orbiting in the region of space between Mars and Jupiter, and most of them smaller than about ten kilometers in radius. From studying the distribution of asteroid sizes it is possible to estimate the overall population of asteroids, including those which because of their small size have not yet been discovered. (Our surveys of the main asteroid belt are probably complete only down to a diameter of 10 km.) It is clear that the smaller bodies are the more numerous bodies, and that the largest number of asteroids are to be found in size ranges too small to be easily detected yet from Earth.

This conclusion is especially important when we examine the small subset of these asteroids which are known to follow eccentric orbits that carry them in from the asteroid belt to cross the orbit of Earth. Several thousand such objects are already known, and there is an active research program whose goal is to be able to track the orbits of at least 90% of the computed population. Because they come closer to Earth, many such Near Earth Objects (NEOs) as small as a few tens of meters have been observed; using the same sort of size distribution statistics one can estimate that many thousands of such objects, similar to that which exploded over Chelyabinsk, remain to be found. Already we are finding small NEOs arriving as close to Earth as the orbit of the Moon at a rate of about one a month.

Obviously, the smaller the object the more numerous they are; but the harder they are to discover, and the more difficult it is to be able to predict when one of that size might arrive close to Earth. In planning to find an asteroid that might be exploited, a size of about 1 km diameter seems like a good first guess.

A simple, very naive calculation may help set the stage for us to appreciate the scale of the resources being talked about. First, for ease of calculation, let us simply assume that such an asteroid is spherical; thus the volume of a 0.5 km radius asteroid is about 0.5 x 109 cubic meters. If it is a typical S type asteroid, made of ordinary chondritic material but battered into a rubble pile that is 40% empty space, we would expect it to have a bulk density of about 2x103 kg/m3 and thus a total mass of 1012 kilograms.

What material in an ordinary chondrite might be considered worth exploiting? Recall that about ten percent of the mass of such a meteorite is metal, primarily iron and nickel but also containing significant traces of more valuable metals such as gold, platinum, copper, silver, or zinc. Continuing our naive calculation, we can assume that our typical asteroid has these metals in the abundances found in meteorites; we then look up what these metals sell for typically on the open market today; and finally add up the various monetary values to arrive at the worth of the entire asteroid.

The result looks startling. The iron alone constitutes 15 million metric tons of material; given a value of a few hundred dollars per ton, one can easily see that it is worth on the order of about ten billion dollars.

In fact, at current values for rare metals, the iron makes up about half the value of the metals in total, since the more valuable metals are of course much rarer. Still, one might expect that disassembling a 1-kilometer asteroid made of ordinary chondritic material would yield metals worth on the order of $20 billion.

A casual perusal of this calculation shows that it is indeed naive. Obviously it does not reflect at all how the markets for these raw materials would be affected by the arrival of such a new and plentiful source. Nor it does not take into account how expensive it would be to actually rendezvous with such an asteroid, disassemble it, and bring the materials back to Earth. The latter is more difficult than it might seem at first glance; the relentless

laws of celestial mechanics tell us that an NEO which comes into a close pass to Earth, and thus easy to reach at that time, will cross Earth's orbit again many, many times before actually encountering Earth again at the same time. It may take tens to hundreds of years before the asteroid returns close enough to Earth to allow for the easy return to us of whatever material has been dug out and packaged for our use.

Going after a smaller NEO would undoubtedly reduce the cost of exploitation, and allow it to be exploited while it is still close to Earth. With the same simple assumptions, what would be the value in a 15-meter ordinary chondrite, similar to the meteoroid that exploded over Chelyabinsk? Remember that an object this small would probably not be a rubble pile (rather, something that small is probably one of the bits of the rubble). Thus it would have a higher density, increasing the amount of valuable metals to be found within it. Even with that advantage, though, we can calculate that it would likely have a mineral value of only about $150,000… hardly worth the investment of millions of dollars for a spacecraft to go and capture it. Indeed, it would be worth more if one were to sell bits of it to meteorite collectors at the going prices for common meteorites.

Of all the questionable assumptions in the calculation above, however, the one that is most certainly not correct at least at the present time is that the most valuable use of such NEO resources would be resources for terrestrial consumption. In fact, the most prized resources in the short run may not be metals to be sent back to Earth, but water and oxygen that could be used to make rocket fuel in space, and thus support the exploration or indeed human life in space itself. That being the case, C type asteroids that are made of water-rich carbonaceous chondrite material are particularly prized for their OH content (recall that such asteroids are the targets of two ongoing space missions).

This is the motivation currently driving the nascent space resources community. Among the companies currently set up for this work include Deep Space Industries, Kepler Energies and Space Engineering, and Planetary Resources; a look at their web pages goes into great detail about what they hope to do, and how they hope to do it.

The US National Aeronautics and Space Administration (NASA) is actively working on the basic engineering of space mining a program; their web site discusses topics such as how to attach the equipment to the asteroid surface under very low gravity, how to excavate the regolith, and possible ways of extracting metals.

Luxembourg and other small countries, including the United Arab Emirates and the Isle of Man, are setting themselves up as hosts for entities looking for a favorable place to incorporate themselves. For example, Luxembourg has established a "Space Cluster" to promote space business and in September 2016 a meeting titled "Asteroid Science Intersections with In-Space Mine Engineering" was held at the University of Luxembourg, attracting both space scientists and planetary astronomers.

Social Implications

The short-term use of space resources will be to make it easier to travel in space. But the long-term purpose of such space travel is, ultimately, the exploitation of space for human purposes. These activities can range from scientific explorations, to tourism, to health care in low gravity, to manufacturing that makes use of non-stop solar energy… and nearby, easily exploitable space resources.

Our near Earth environment, with a steady supply of NEOs, would provide an essentially unlimited supply of resources while solar power in space, not limited to the vagaries of weather or a day/night cycle, would provide the energy to manufacture these resources into useful products. Mining and manufacturing on Earth puts an enormous stress on its environment; moving mining and manufacturing off-planet would preserve the natural setting and beauty of our irreplaceable planet. All of these benefits make the eventual exploitation of space resources very attractive and in some ways necessary to be able to sustain our lives at a level of industrial sophistication that, at present, comes with a terrible environmental cost.

Note that both resources of space would be available to anyone who can get to them. Space is uninhabited, which means that such resources are not under the control of whoever happens to be living where they are found. But for this very reason, space resources will inevitably wind up exclusively in the hands of space-faring multi-nationals. Competition for the most easily exploited NEOs will require new ways of deciding what constitutes legitimate claims, and new ways of arbitrating such claims (similar issues exist already in the ownership of meteorites, where every nation has a different set of laws and standards). The best precedent for how to proceed is probably the already existing law of the sea.

If space resources replace resources mined on Earth, what will be the effect on the economies of those nations, often among the poorest, who rely on raw material exports to support their economies? If resources are obtained in space, undoubtedly most of the actual labor will be done by robots, pre-programmed and monitored remotely. This means that there would be little opportunity for employing the unskilled labor. What happens to those laborers, who are often among the poorest members of our society?

In his Encyclical *Laudato Si'*, Pope Francis has drawn an important light on the social and moral issues that accompany technological change, even change that on the whole has great promise to improve human life in the long run. Eliminating the jobs connected with extracting resources on Earth, jobs usually associated with areas of significant poverty and lack of opportunities, will undo the social structures that give those communities a cultural identity and sense of meaning of life. What will happen to them? Where will they go, and how will that affect the culture and economies of the places that receive them?

What can we think to do, now, to prepare for a future where these disruptions are likely to take place?

Conclusions

The research into meteorite physical properties at the Vatican Observatory was begun with a simple goal, to help better characterize these solar system materials and perhaps provide data useful to others who wish to understand the origin and evolution of asteroids. What has happened, however, is that our data have turned out to have a much wider utility than we could have imagined. In particular, they play a central role in characterizing asteroids that are potential targets for resource exploitation.

The immediate use for asteroid resources almost certainly will be to extract water and oxygen, whose utility is obvious not only for sustaining life in space but more immediately as a resource to produce rocket fuels to allow for more extensive exploration… fuel that otherwise would have to be lifted out of Earth gravity at enormous expense and inefficiency. It is not likely that any particular social disruption would come from these uses of space resources. But it must be acknowledged that the long-term result of making it easier to live and travel in space, will be the eventual exploitation of resources like those described here. What eventually will be the most disrupting action of our activities in space we cannot yet judge, any more than we could guess what our meteorite data would lead to.

Finally, to echo *Laudato Si',* we must correct the present disparity between excessive technological investment in consumption and insufficient investment in the human family. Our goal must be to prioritize stability and avoid unnecessary disruption in the social fabric that inevitably accompanies technological change (and indeed would occur if we failed to use technology to respond to the changing needs of society). The criterion for how we judge our actions, ultimately, is love. Love, in our political, economic, and cultural spheres, must become the highest norm of our actions.

[1] Consolmagno *et al*., *Chemie der Erde* 68, 1-29 (2008)*;* Flynn *et al*., *Chemie der Erde*, in press.