The Peaceful Uses of Solar System Resources: Opportunities and Issues[*]

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In June, 2018, I had the honor as director of the Specola Vaticana (the Vatican's astronomical observatory) of leading the Holy See's delegation to the United Nations UNISPACE+50 conference in Vienna, celebrating the 50th anniversary of the first such UN conference on the peaceful uses of outer space.

Leading up to that meeting, in March 2018 the Specola Vaticana had helped organize a workshop at our headquarters in the Papal summer gardens outside of Rome to discuss the broader issues of the peaceful uses of space and space technology. The seminar was attended by 30 participants from nine countries, including scientists, diplomats, educators, and representatives from space-related industries. At UNISPACE+50 I summarized the results of that workshop:

> *In seeing the Earth from space, we realize that our own borders are insignificant in comparison. The Earth's atmosphere is a global environment that needs to be protected by a global vision of this limited, shared natural resource and must be utilized for the benefit of all humankind.*
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> *Space Accessibility should be understood to include accessibility to space-derived data and services for everyone on Earth, not just accessibility to the outer space environment for conducting research.*

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> *The discussions at the [March 2018] Seminar noted the numerous opportunities for the public's involvement in space science provided by the space community and the need for greater engagement with the public, as well as greater transparency by countries in the sharing of data, policies and motivations for space research.*
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> *We need to reflect on how we can transform the paradigm of the space economy from one of making very expensive space services and products available to a few people, to one that harnesses the abundance of space-derived data and services for the good of all.*

The conclusion of the Vatican UNISPACE+50 statement looked back on the UN's landmark 1967 Treaty on the Peaceful Uses of Space:

> *All nations share a common border with outer space, so all nations would be equally near such an area of conflict. Conflict in space would inevitably escalate tensions on Earth, and the effects of armed conflict in space would affect all present in outer space, whether they are combatants or not. The Holy See therefore, implores all States to maintain the peaceful uses of outer space – for the good of all and our one common home.*

This conference held a particular personal meaning to me because my research at the Specola Vaticana over the past twenty five years has been centered on understanding the origin and composition of asteroids in our own solar system, bodies which in the near future may play a key role in the exploitation of space.

Such exploitation raises both opportunities and moral issues. This was the topic of my presentation at the Pontifical Academy of Sciences Plenary Session of 2016, from which this article has been adapted.

Asteroid Research

My research for many years has been on asteroids: small rocky bodies 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 that formed the planets in our solar system. We have reason to believe that meteorites, rocks seen to fall from space, represent samples of those asteroids. The main motivation behind our work at the Specola Vaticana is to understand the formation of the planets, 4.6 billion years ago; the study of meteorites can give us insights into the asteroids and thus 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 death of the dinosaurs 65 million years ago; our best estimates now suggest that such enormous impacts only occur once in a hundred million years. 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, a 30 meter diameter asteroid passed closer to Earth than the orbital altitude of geosynchronous satellites. On the same day, a completely unrelated 18 meter sized meteoroid hit the Earth's atmosphere and exploded over the Russian city of Chelyabinsk; following that event, 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 one million inhabitants. It is estimated that objects similar to the Chelyabinsk impactor probably hit the Earth at least once a decade.

There is a third motivation for studying asteroid composition and structure, however. Within the next few decades these asteroids may well become new sources of natural resources. In the latter months of 2018, two separate spacecraft probes, one by the Japanese space agency JAXA and the other by the American space agency NASA, arrived at asteroids whose small size and near-Earth orbits make them candidate asteroids that might be exploited for minerals in the not too distant future. Both missions are designed to return to Earth small samples of these bodies, for scientific research. The technology already exists, at least at a small scale, for mining these bodies. 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 in our laboratories. 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 this meteorite-asteroid connection. Some two dozen fireballs have been imaged from multiple locations, with enough detail to allow one to trace their orbits back to the asteroid belt. The material recovered from these fireballs are typical meteorites.

Another strong line of evidence is the observed colors of the asteroids. The asteroid spectra match the colors measured in meteorites.

The most telling evidence, of course, comes from samples returned from asteroids themselves. The most common stony meteorites can be classified generally into two main groups, ordinary (made of dry stone) and carbonaceous (dark and sometimes rich in carbon and water). A Japanese mission to the small asteroid Itokawa returned to Earth in 2010 with small particles of dust, whose chemical compositions exactly match samples of the “ordinary” meteorite group.

Just as meteorites come in two types, the most common asteroids can also be sorted into two main groups, “S” and “C”, based on their colors and brightness. The assumption is that the brighter, reddish-colored S type asteroids are the source of the ordinary meteorites, while dark C type asteroids are where the carbonaceous meteorites come from. Itokawa is an S type asteroid. Meanwhile, the two sample return missions currently orbiting asteroids, as mentioned above, are both targeted to sample C type asteroids. By the early 2020s we will have solid data to confirm the connection of these different asteroid types with the different classes of meteorites.

Asteroid Physical Properties

The classification of meteorites by chemical type is the fruit of a century’s worth of painstaking work in collections around the world. However, while such work was progressing especially in the years following the Apollo moon missions, the measurements of the physical properties of meteorites (density, porosity, magnetic susceptibility, heat capacity, thermal and electrical conductivity) only began in earnest about 25 years ago at laboratories in Finland, Canada, Japan, and our group at the Vatican. In particular, at the Vatican we have been able to devise new ways of measuring meteorite physical properties on whole rocks without cutting or damaging the samples.

Knowing how the meteorites are physically put together is essential for understanding the physical evolution of the planets. But it also has given us a new tool for a completely different sort of endeavor. Whereas the color of an asteroid only characterizes its surface, bulk physical properties such as density allow us to examine the content of the entire body. When we compare our measurements of the densities of the meteorites we have measured with the densities of the asteroids, we find that just as carbonaceous meteorites are more porous and less dense than ordinary meteorites, likewise the C type asteroids are systematically less dense than the S types. But in both cases, the asteroids are 25% to 50% less dense than the meteoritic material from which we believe they are made. What does this mean? Our inference is that asteroids today are not solid bodies, but rather loosely packed piles of rubble.

This tells us that the asteroids we see today have probably been broken apart and fallen back together many times over the history of the solar system. But just as importantly, it also tells us how much material we can actually expect to find in an asteroid of a given size, and what to expect when we send a robot to dig up its surface.

Mining Asteroids

About half a million asteroids have 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 all the asteroids, including those that are still too small to have yet been discovered (generally those smaller than 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 the range of sizes that are still too small to be easily detected from Earth.

This conclusion is especially important when we examine the small subset of these asteroids which are known to follow orbits that carry them in from the asteroid belt to cross the orbit of Earth. Several thousand these 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), some as small as a few tens of meters across, have been observed with telescopes and even by radar. Already we are finding, at a rate of about one a month, small NEOs arriving as close to Earth as the Moon. We estimate that there must be many thousands of objects similar in size to that which exploded over Chelyabinsk, but which remain to be found.

What material in these asteroids might be worth exploiting? We can make a first guess by assuming that the asteroid compositions match those of our meteorites. About ten percent of the mass of an ordinary meteorite is metal, primarily iron and nickel but also containing significant traces of more valuable metals such as gold, platinum, copper, silver, or zinc. If we assume that a typical asteroid has these metals in the abundances found in meteorites, we can look up what these metals sell for typically on the open market today, and add up the various monetary values to arrive at the worth of the entire asteroid.

The result looks startling. In even just a one-kilometer diameter asteroid, the iron alone constitutes 100 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 tens of billion dollars. And in fact, at current values for rare metals, the iron makes up only about half the value of the metals in total, since the metal also includes the much rarer valuable metals like platinum and gold. One might expect that disassembling a one-kilometer asteroid made of ordinary chondritic material would yield metals worth more than $20 billion.

However, a casual perusal of this calculation shows that it is quite naïve. 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.

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 meteorite similar to the meteoroid that exploded over Chelyabinsk? An object this small would probably not be a rubble pile; 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 $100,000… 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 is that the most valuable use of such NEO resources would be to extract raw resources like metal, to be returned to Earth for terrestrial manufacturing. Raw materials are not the only resource to be found in abundance in space, after all; solar energy is also available full time. If we can build robots to mine the asteroids, why not build other robots using this solar energy to process and refine the materials? And indeed a third generation of robots could use those refined materials, and that energy, to manufacture useful goods in space for consumption both in space and on Earth.

But 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 material would be particularly prized. (That is one reason why such asteroids are the targets of the two current space missions.)

This is the motivation currently driving the nascent space resources community. Over the past five years, a number of corporations have been launched to perform such mineral exploitation, with names like *Deep Space Industries,* and *Kepler Energy and Space Engineering,* and *Planetary Resources*. A look at their web pages shows great detail about what they hope to do, how they hope to do it… and the difficulties involved in maintaining financing for such speculative activities. As of this writing, both Planetary Resources and Kepler Energy are facing uncertain futures.

The US National Aeronautics and Space Administration (NASA) is also actively working on the basic engineering of space mining. 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 space resource 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.

Philip Metzger, an expert on space resources at the University of Central Florida, has an even more provocative take on the topic. While acknowledging that “real value of space-based mining will be to create a space-based industry that benefits all of us,” in a recent article on space resources he concluded, “the primary import from space will be massless photons carrying data and energy.”

In fact, this is already the case. Ninety nations already have a space-exploration agency of their government registered with the UN. Of these, only about a dozen nations (and international entities like ESA) have put satellites into orbit, though a growing number of multinational private corporations are also launching satellites. But the majority of the work done by the space agencies of small nations is the exploitation of space-based data such as orbital images. Images from satellites can provide detailed and accurate maps of land use and resource availability to countries without the resources to have continuous on-the-ground reporting, especially from inaccessible areas. There is now so much data available that anyone with a modest computer can do valuable work to analyze and exploit that data.

Social Implications

By consuming water-rich asteroids to make rocket fuel from their oxygen and carbon, 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.

Mining and manufacturing on Earth put an enormous stress on its environment; moving mining and manufacturing off-planet would preserve the natural setting and beauty of our irreplaceable planet. And data about Earth can be obtained and transmitted by satellites more quickly, and cheaper, than by traditional methods. 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 the resources of space are 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 likely wind up exclusively in the hands of space-faring nations and multi-nationals.

Furthermore, though space seems limitless, in fact the regions where Earth satellites orbit is already getting crowded. Debris from failed satellites can damage other satellites. Even perfectly functioning satellites can interfere with each other. And while private industry is a boon when it comes to financing the uses of space, investors want some assurance that their returns — be it data or space minerals — are protected from piracy.

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.

How can this coordination be organized? And even more critically, how can it be enforced? One way to encourage this cooperation is to make as many people as possible stakeholders in the enterprise. The more people who have a stake in the use of outer space, the more they will be willing to take care of it.

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. 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?

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 plan 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's 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.

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.