A STAR'S COMPANIONS

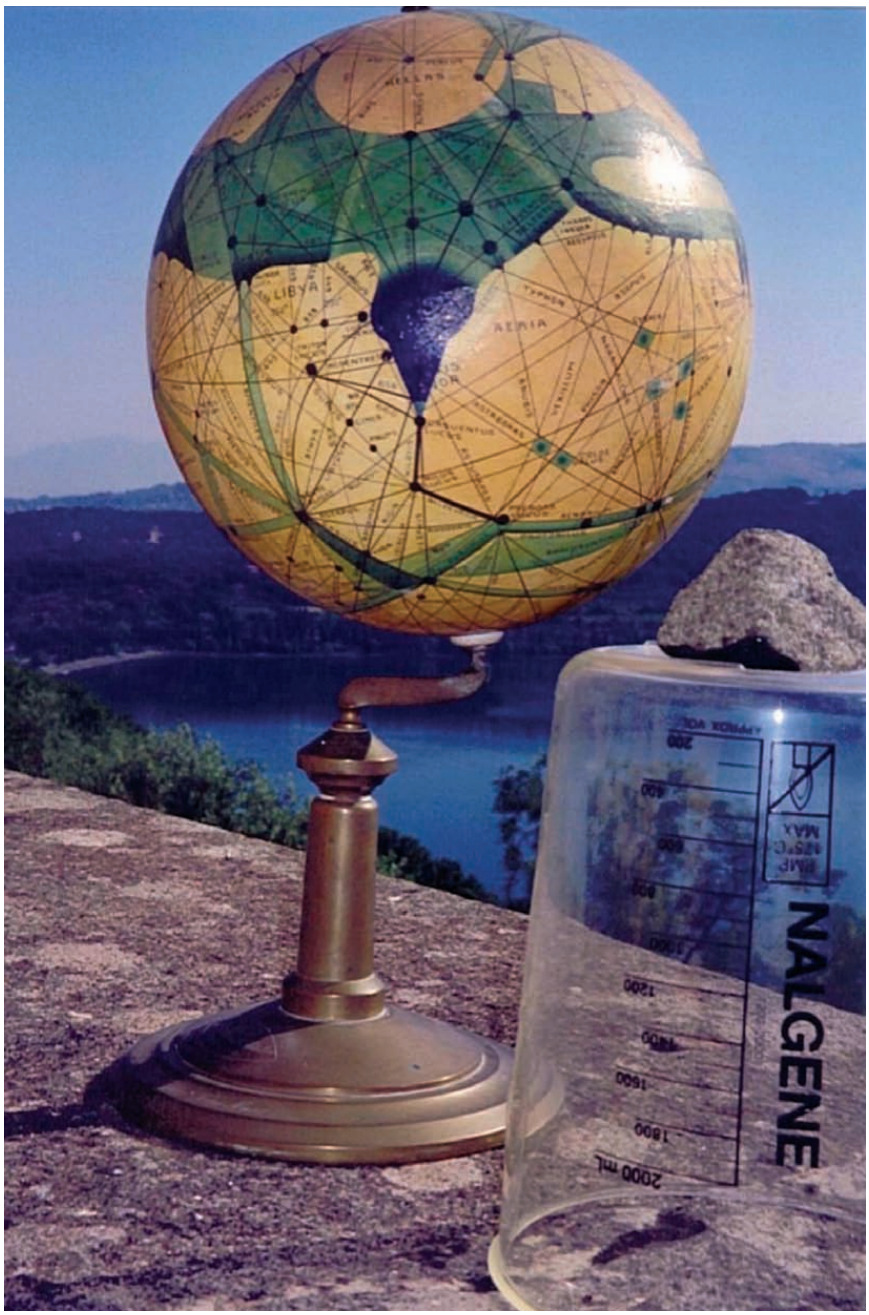
Meteorites: Aliens at the Vatican

• Br. Guy Consolmagno S.J. •

Introduction

At the Vatican Observatory you'll find a thousand aliens: meteorites, rocks from outer space that have fallen to the surface of our Earth. In many cases they'd been seen to fall, making a bright fireball through the air, and collected near craters formed when they'd hit the ground. Others are stray bits of iron, or grayish rock, that don't look like anything from around here. Each bears the name of the place on Earth where they'd been found. Some, like Sacramento Mountains, are metallic iron, though rich also in nickel and other metals, etched and polished to show a pattern of interlocking crystals. Some are stone: Agen, like most of these, is made of millimeter-sized balls of rock called *chondrules*, while other stony meteorites, like Nakhla, look like flows of lava from some extraterrestrial volcanism. And a third group, like Fukang, mix iron and stone in roughly equal proportions.

Regardless of their structure, though, their chemical compositions



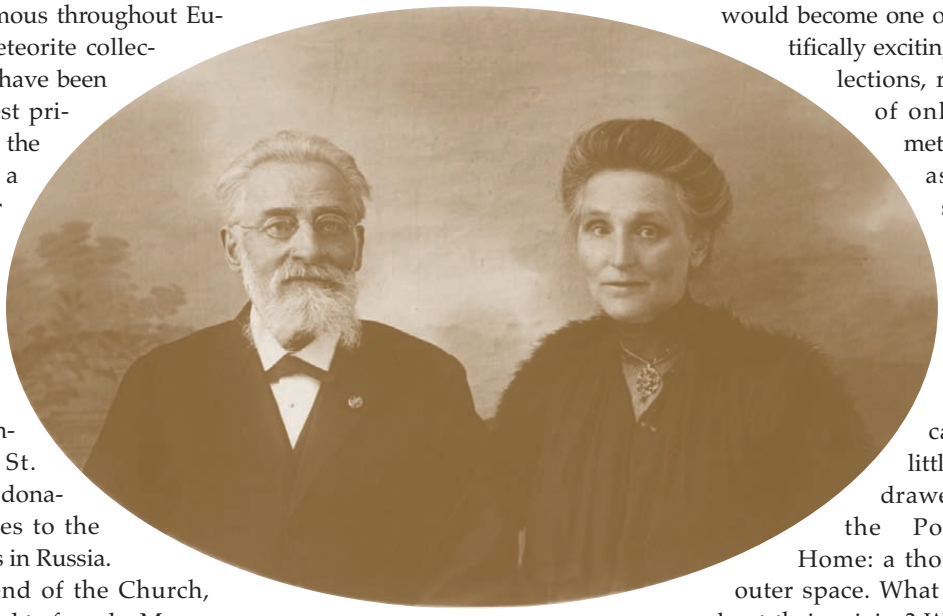
Right *A globe of Mars (hand-painted by Ingeborn Bruhn c. 1916) shows the original home of the Nakhla meteorite, Mars.*

and elemental isotopes differ from any rock on Earth. They really are aliens from outer space.

The core of the collection was put together by a nineteenth–century French nobleman, the Marquis de Mauroy. Adrien-Charles, Marquis de Mauroy (1848-1927) was a distinguished agronomist and "gentleman-scientist" of the old French nobility, a life member of the Société Française de Minéralogie who served three terms as its vice president. His collection of minerals was famous throughout Europe, and his meteorite collection was said to have been the second largest private collection in the world. He was a great supporter of schools and scientific institutions; for instance, Czar Nicholas II awarded him the insignia of a Commander of St. Stanislas for his donation of meteorites to the Institute of Mines in Russia.

A great friend of the Church, the Marquis hoped to found a Museum of Natural History at the Vatican. To that end, he first proposed in 1896 to donate a collection of 1800 rocks and minerals, and a library of some 400 books and monographs about them, to the Vatican. At that time, however, the Observatory (where they were to be housed) had only recently been refounded by Pope Leo XIII and was located in cramped quarters, primarily the Tower of the Winds; the Marquis was thus asked to postpone his donation.

In 1905, a subset of the de Mauroy meteorite collection (about 150 pieces, mostly duplicates and smaller samples) was donated by the Marquis. But his dream of a natural history museum never materialized. When the Specola moved from Rome to Castel Gandolfo in 1935, his widow Marie Caroline Eugénie donated the remainder of his collection. In 1973, the terrestrial minerals were given in permanent loan to the Geochemical Institute of the University of Vienna; but the meteorites stayed at the Vatican.



Above *The Marquis de Mauroy, who collected the meteorites that became the Vatican collection, and his wife Marie Caroline Eugéne who donated the collection to the Vatican at the death of her husband.*

In addition to the Marquis's collection, the Specola early on had two other important meteorite donations. An iron meteorite first identified as Angra dos Reis (iron) but now known to be the main mass of Pirapora was donated to Pope Leo XIII and was transferred to the Specola Vaticana in 1917. And in 1912, John Ball, the acting head of the Geological Society of Egypt, kindly sent a 154g piece of the newly fallen meteorite Nakhla. Little did he know that by the 1980s this meteorite would become one of the most scientifically exciting falls in our collections, representing one of only a handful of meteorites identified as pieces of the surface of Mars.

Collected over a period of some two hundred years, now these "aliens" sit in carefully labelled little plastic bags in drawers in a room in the Pope's Summer Home: a thousand pieces of outer space. What can they tell us about their origins? What can they tell about the places they've been, and the things they have seen?

Measuring the Meteorites

Starting at about the time of the exploration of the Moon in the 1960s, the chemical study of meteorites has made huge advances. Techniques developed for the study of lunar rocks have been applied to meteorites with great success. Electron microscopes allow one to see the crystals in slices of a meteorite at a scale of better than a millionth of a meter, and the radiation emitted when the electrons hit can tell you, crystal by

crystal, what elements are present. In addition, we can now boil off individual atoms from each crystal and look for the particular isotopes produced by the radioactive decay of certain well-studied elements. By knowing how fast the radioactive atoms decay, and counting the number of the daughter isotopes have accumulated there as the result of those decays, you can calculate how long the crystal has been frozen into its current form and able to collect those atoms. The precision of these measurements is now so good that you can see differences in age of only a million years between rocks that, like most meteorites, are 4.567 billion years old.

But such experiments require expensive and complicated equipment – and a trained staff of technicians to keep it all operating properly. When I arrived at the Vatican Observatory in 1993, I realized that we could never duplicate such a lab and stay anywhere within our budget! Besides, those experiments were already well underway in other labs around the world. What I needed to do was to find a range of experiments suitable to the nature of our collection and our limited resources.

***Above** A formal portrait of the Martian meteorite that fell near the Egyptian town of Nakhla in 1911.*
Photo credit: *Alberto Pizzoli.*

The collection had been put together as an amateur's collection: it had mostly small pieces, very few pieces of them "main masses" with material to spare for destructive experiments. But it included a remarkable range of different meteorites and meteorite types; this suggested that I look to do experiments that surveyed characteristic across meteorite types.

On the other hand, I realized that the Marquis had collected most of these samples more than a hundred years ago. Meteorites are known to be filled with tiny flecks of metallic iron; that's one of the chemical traits that distinguishes them from Earth rocks. Earth's atmosphere (and water) attacks this iron, and over time turns it into rust. What sort of measurements could I do that would not be affected by this rust?

Densities

In my earlier career, before I became a Jesuit brother and was assigned to the Vatican Observatory, much of my research had been based on trying to make mathematical models with a computer to describe how small bodies like asteroids and moons evolve over time. There are all sorts of interesting geological processes that can happen even in such small bodies: for example, the insides of icy moons can melt, forming salty oceans between an icy crust and a rocky core – even with the chance that there might be some sort of bacteria (or fish? or dolphins?) swimming around in those oceans! But to make these models, I had needed to know some basic traits about the stuff that moons and asteroids are made from. The characteristics of ice were well known, but the rocky material in these bodies was less well studied. The best guess has always been that whatever rock is out in the solar system is probably not all that different from the meteorites… which, after all, we know come from that region of space.

So what were the kinds of data I wished I had for my models? I wanted to know how well the rocks collect and conduct heat; how likely they were to flex and change shape under a variety

of different stresses. But most basic of all, I really wanted some good numbers for the density of these rocks.

Think about how you used to test the presents under the Christmas tree when you were a kid. You would pick up one wrapped box after another, and judging from its "heft" you could guess which boxes might have chocolate, and which ones just had new socks. That heft is in fact what we call density. Water has a density of one gram per cubic centimeter; iron has a density near eight grams for the same volume. But there are many different kinds of rocks, and their densities can range from two to five grams per cubic centimeter. What's the appropriate value to use when you are making a mathematical model of a moon or asteroid? We know that the meteorites come from the asteroid belt; presumably their density would be what I wanted.

But in fact it was not at all easy to find a density for many types of meteorites. In part, that was just one of those measurements that no one had gotten around to doing. But digging a little deeper, I began to see why it was so hard to measure.

Above *The Agen H5 meteorite is a typical ordinary chondrite. It fell in France in 1814. The interior is gray while the outer surface was burned with a black fusion crust by its rapid decent through the Earth's atmosphere. The crust has since turned brown by reactions with Earth's moist atmosphere.*

Density is mass divided by volume. You can measure the mass easily enough; just weight the sample. But volume is trickier, because meteorites are irregular in shape.

Of course, Archimedes had figured out how to measure such a volume some 2500 years ago. Asked to test the density of the king's crown (to see if it was really pure gold, or just gold covering a less-dense base metal) he pondered the problem while taking a bath; and seeing how the bathwater rose as he was lowered into the tub, he got the bright idea of measuring the volume of the water spilled out of a full bucket when the crown was immersed in it. (He was so excited at this idea, the story goes, that he jumped from his bath and ran naked down the streets of Syracuse, shouting "Eureka!") A modern variation of this idea – mathematically it comes to the same thing – is to weigh the rock first in air, dangling from a string, and then see how the weight changes when the rock is dangled into water.

But I could see, there was trouble dipping meteorites into water. I knew that my meteorites were liable to rust just sitting in air. To dunk them in water risked doing permanent damage to their chemistry... not to mention the risk of contaminants from the water getting into the rock, which might invalidate any future chemical measurements. (Modern probes are so sensitive that you need to remove your rings before handling meteorites, for fear of stray elements from the metal jewelry contaminating the samples.)

To prevent such contamination, perhaps you could wrap the meteorites in plastic. But I tried that out on a pile of sugar cubes (being cubes, I could measure their volume directly) and no matter how tightly I tried wrapping the plastic the cubes tended to come out soggy. I read papers where scientists in Japan had actually just carved some of their meteorites into perfect cubes; but I didn't want to carve up my samples, and besides, how could I tell if that cutting might not change the structure of the meteorites, introducing internal cracks that might change their density?

But then I had my own *eureka* moment over a cup of cappuccino. Every morning at ten o'clock, all work stops

at the Observatory and we gather in the kitchen of the Jesuit residence to take a coffee and chat with each other about our work (and the local football team). It's one of the perks of living in Italy. But while I was pouring my sugar into my cappuccino, it suddenly occurred to me that a powder like sugar behaved much like a fluid. If I poured it over my meteorites, it would fit evenly around all the irregular corners and crannies, but it wouldn't actually react with or contaminate the rock.

Take a plastic measuring cup, measure its volume, then fill it with your powder and weigh it. The weight, divided by the volume, tells you the density of the powder. Now, insert the meteorite in the cup, fill the rest of it with the powder, and weigh it again. The difference between the two weights, with a little bit of algebra, can eventually lead to the density of the rock compared to that of the powder. I tried it out, and it seemed to work!

Later, visiting our Observatory's Tucson offices, I described my method to my friend and colleague, Dan Britt, who was working then with the Mars Pathfinder mission at the University of Arizona's Lunar and Planetary Lab.

Dan was interested in meteorites because he wanted to compare their densities to asteroids. From missions to Mars, we had gotten density values for the little Mars moons, Phobos and Deimos, which everyone agreed were probably are captured asteroids. And the Galileo spacecraft had obtained a density for asteroid Ida while passing through the asteroid belt on its way to Jupiter. (Galileo's images gave us a measure of Ida's volume, while a series of pictures showed the motion of its little moon Dactyl, which could be used to calculate its mass.) In the next few years, a number of other missions to asteroids were being planned. But what good is an asteroid density if you don't have any meteorite densities to compare them against?

We compared the different ways of measuring meteorite porosity. "The trouble with using water isn't just the contamination," he pointed out. "Rocks like meteorites can be riddled with cracks and other pore spaces. The water gets into some of those spaces, but you never know just how much of the pores spaces get filled. So I was talking to a geologist working on measuring the density of core samples.

Above *Iron meteorites, like this large slice of San Francisco Mountains, show a complex crystal pattern when etched with acid. The crystals indicate the high nickel content in the metal.*
Photo credit: *Alberto Pizzoli*

They use a device called a pycnometer. Instead of water, it uses helium gas. Helium is completely inert, so there's no contamination."

He explained how it worked. The rock is sealed in a chamber of known volume, flushed with helium at room pressure. A second chamber of known

volume with helium at, say, two atmospheres pressure, is attached to the first chamber. Open the valve between them and measure the final pressure turns out to be. The bigger the rock, the more space it takes up in its chamber, the less room there is for helium, and so the higher the final pressure.

"But the best part," Dan told me, "is that the helium gets into *all* the cracks. It tells you the volume of just the rocky part of the rock."

But I realized that my powder method would measure the volume of the rock including any pores spaces. "Isn't that the volume of the meteorite really want, to compare with asteroids?" I wondered.

"Actually, you want both," he replied. "The difference between the two volumes is the volume of the pore space: this way, you can measure the porosity of the meteorites."

Sand on a beach is fifty percent empty space. Typical sandstones can be as much as thirty percent pore space. "I've searched the literature for porosity measurements of meteorites," he told me, "and they're darn hard to find. One of the most common classes of meteorites, LL chondrites, has had only two porosities published. One was three percent, the other was thirty percent. Which are we supposed to believe?"

Once I had explained my powder method, Dan immediately went about improving it. Instead of plastic cups and sugar, he obtained flat-topped beakers and 40–micrometer diameter glass beads. Unlike other powders (like sugar) the beads were round and poured around the rocks much more smoothly.

In April, 1996 I invited Dan and his family to visit us in Castel Gandolfo; he brought the pycnometer and together we set up the lab. For the next three months I measured nearly a hundred different meteorite samples from the Vatican collection. The first time I presented the results, at the annual meeting of the Meteoritical Society in Berlin, a grand old man of the field took me aside. "Why are you doing density measurements?" he asked me. "Nobody does that!" That, I thought, was precisely the idea.

But as we gathered more data and began to see patterns in the porosity, eventually people began to get interested. Our first results were published in the journal *Meteoritics and Planetary Sciences*. Soon our technique, and our measurements, became a standard source for the community. Ten years later, we were invited to review our work in a lengthy article for the prestigious journal *Chemie der Erde*. It's quite ironic that we would publish in a journal whose title translates as "chemistry of the Earth", since our measurements were about the physical nature, not the chemistry, of our samples… and those samples were definitely not part of the Earth!

This great interest was spurred in no small part by fortuitous good timing. Not only were spacecraft measurements providing a handful of asteroid densities, but just as our work was getting published, improved telescope techniques on Earth had led to the discovery of dozens of asteroids with small moons. Once you can see the asteroid pulling the moon around itself, you can calculate its mass – the hardest number to get for an asteroid density. And it turned out, these bulk density measurements indicated that compared to our meteorites these asteroids were 20% to 50% empty space: porous on a scale bigger than the porosity within the meteorites themselves. Asteroids are not solid rocks orbiting the Sun; they are at the least heavily fractured bodies with deep cracks running through them. And some of them are probably piles of rubble, as porous as a bucket of beach sand.

One clear trend in our data is that bodies larger than about 10^{20} kilograms in mass, or about 500 kilometers in diameter, have no porosity at all. They must have enough gravity to pull themselves into a spherical shape. This could be the basis for defining the boundary between small solar system bodies like asteroids and comets, and the newly defined class of Pluto-like bodies called dwarf planets.

Digging deeper into the data, recently we have begun to see an interesting trend. The asteroids from the inner part of the asteroid belt tend to be about 20% less dense than the "ordinary chondrite" meteorites which they resemble; and those meteorites are full of microcracks that add another 10% of porosity. But asteroids further away from the Sun are much darker, like "carbonaceous chondrite" meteorites.

They are also much more porous – as much as 50% empty space – and the meteorites themselves have another 25% porosity. As one goes to the colder parts of the the solar system, solid material gets to be quite fluffy indeed. And this is confirmed by a handful of measurements indicating that the nuclei of icy comets may be as much as 80% empty space!

Not only does such a structure for an asteroid have a profound significance for our understanding of how the solid material that eventually made up planets like Earth was processed in the early solar system. It also has very practical implications.

As a number of Hollywood movies have tried to dramatize, there is a real (if small) threat that an asteroid in an eccentric orbit could someday hit the Earth. We certainly see small bits of asteroids hit Earth today: the meteorites themselves, and more commonly meteors or "shooting stars" as Fr. Kikwaya describes in his chapter. Smaller ones are more common, but bigger ones do hit. But if we knew that such an asteroid was heading our way, how could we deflect it? Hollywood's answer is to send Bruce Willis up with a big bomb. But a rubble pile is already broken into pieces; a bomb will just absorb the blast, squeezing and rearranging the rubble without dispersing anything. A more reasonable strategy might be to put a small device on the asteroid surface that gathers up the loose rock and spits it out in one direction, slowly deflecting

Above *Stony iron meteorites, like this slice of Fukang, combine basaltic minerals with iron. The translucent green crystals visible here are olivine (known as peridot when in gem form) while the metal has a composition similar to the iron meteorites. That both the dense metal and the less dense olivine crystalized together without separating indicates that these meteorites were formed in a region of very low gravity.*

the rest of the asteroid the other way and thus moving it out of its collision path.

Pennies from Heaven

But asteroids are more than just a threat. As we noted, there are many lines of evidence suggesting that ordinary chondrite meteorites can be derived from a particular type of asteroid, the "S-class", found mostly in the inner asteroid belt. We also know that many such asteroids are in orbits that pass near the Earth. Through 2008, about 5500 such asteroids have already been discovered; 750 of them are larger than one kilometer in diameter. Many of them may at one time or another pass as close to the Earth as Earth's Moon orbits now, a distance that we know we can traverse with manned spacecraft. These are the ones that Hollywood views as threats.

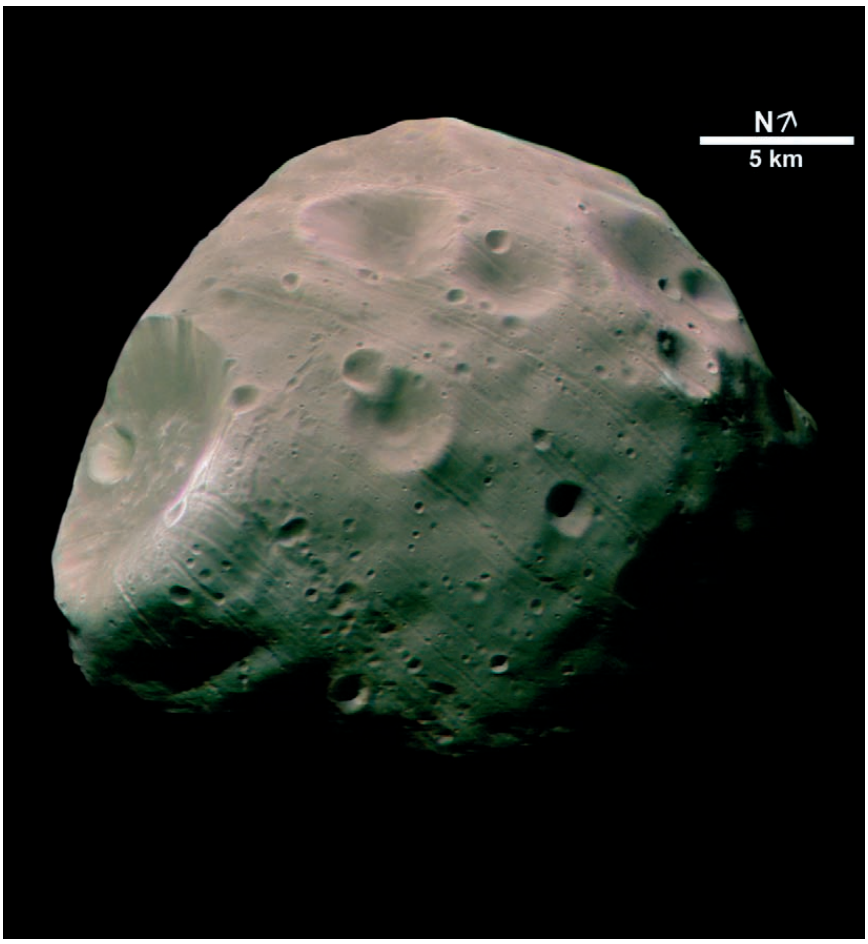
But... consider an asteroid of 10 kilometer radius. The typical S-class asteroid has a density of about 2500 kilograms per cubic meter; so the total mass of one such asteroid is roughly 10^{16} kilograms. If its composition is the same as an ordinary chondrite, it will be about ten percent metallic iron and other siderophile (metallic) elements.

Ten to the fifteenth kilograms of iron – one trillion metric tons – is a thousand times greater than the entire annual output of iron ore everywhere on Earth. The other metallic elements present in such an asteroid, such as gold or platinum, would likewise overwhelm domestic demand for such metals.

A mining expedition that goes out to collect valuable minerals from the asteroids needs to know what sort of surface to expect. We know now that it won't be solid rock. But with the pieces of rubble be grains of dust, or blocks the size of houses? We're still puzzling over that one.

This calculation does show, however, that perhaps the best way to remove the threat of an incoming asteroid is to remove the asteroid itself, bit by bit.

And perhaps someday the Vatican's meteorite collection will be supplemented not only by new samples seen to fall from Earth, but pieces that we've actually gone out and fetched from space itself. Someday, the aliens in our collection may not be immigrants, but souvenirs.



Above *Phobos, the larger moon of Mars, is probably a captured asteroid. You can see evidence for a significant amount of cracks and voids; notice the number of parallel grooves. When you compare the density of small solar system bodies like this one with that of the meteorites we believe come from those asteroids, it becomes evident that most have significant internal voids, and may be rubble piles. Image taken by the High Resolution Stereo Camera on board ESA's Mars Express spacecraft on 22 August 2004.* Credit: *ESA.*

Br. ***Guy CONSOLMAGNO*** *s.j. (USA) is the curator of the Vatican Meteorite Collection at the Vatican Observatory in Castel Gandolfo. An expanded discussion of this topic can be found in his book* Brother Astronomer, *published by McGraw Hill in 2000.*