A Real Death Star
By John McCormick

Following this article are two exclusive interviews conducted by "Perihelion" earlier this month. The first is with Rusty Schweickart, noted Apollo 9 astronaut and research scientist. The second is with Italy's foremost astronomer, Francesco Manca.

FEBRUARY, 2013. A DEATH STAR STREAKED across the sky of central Russia and once again brought the threat posed by meteorites or Near-Earth Objects (NEOs) into sharp focus. This sort of thing always seems to come as a surprise to politicians and the public at large. Most people have little knowledge of history and less interest in science.

In fact there have been other big NEO events in Russia and you might suspect that Russia is hoarding these events to itself, but a quick look at the map shows that in the northern hemisphere Russia covers a lot of territory, while the southern hemisphere is mainly water. So this is a simple matter of geography.

Aster is Greek for star and the more massive of these objects are nothing less than "death stars" because they could end life on Earth as readily as The Empire's Gen. Wilhuff Tarkin blotted out Alderaan.

In 1802, just a year after the first one was discovered, astronomer Sir William Herschel named these astronomical bodies "asteroides," star-like, as close to translating the Greek letters as I can come.

As late as the 1700s, farmers in France who reported rocks falling from the sky were ridiculed by "scientists" of the day and, in fact, the first asteroid, Ceres, which is also the largest yet seen, was only discovered in 1801. This despite the fact that Ceres is

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large enough that it was originally thought to be another planet.

A century later in 1908, a literally Earth shaking event took place over the Tunguska river region of central Siberia. The exact cause of the devastation is still debated but it seems certain that 2,000 square kilometers of forest was flattened by the airburst of some object from space, whether it was a piece of anti-matter, an asteroid, or a comet. But it is calculated to have been as little as 200 feet across.

If the 1908 event had centered above the Washington Monument instead of a vast stretch of uninhabited tundra, most of the District of Columbia would have been depopulated.

More recently, the 2013 Chelyabinsk object exploded 80,000 feet (angels 80 to pilots) to 95,000 feet above ground on February 15, but even at that distance and in very thin atmosphere (which greatly limited any blast effects) the NEO collision still damaged thousands of buildings and injured nearly a thousand people badly enough to require medical attention. At that height, it destroyed itself near the flight ceiling of the SR-71 “Blackbird” spyplane (85,000 feet) which once flew so high that no anti-aircraft missile was capable to reaching it. That means the Chelyabinsk object couldn’t have been hit by an interceptor missile even if one were able to intercept an object moving that fast.

No observatory spotted the object and it wasn’t in any of the NEO databases so we didn’t see it coming. But we couldn’t have done anything about it, anyway.

The object which exploded over Russia last winter and created such a spectacular light show as its remnants burned in the atmosphere was only an estimated 20 feet across and was undetected before it hit the atmosphere—a terrifying event and oversight for those who can picture what would have happened to, say, Moscow or Washington, if the trajectory had been just slightly different. The power of the explosion is estimated to be the equivalent of about one-half megaton of TNT. Remember, all the damage it caused was at a minimum distance of 90,000 feet from the actual explosion.

There has always been an incredible amount of denial among politicians and even many scientists regarding meteor impacts. In living memory, the Arizona meteor crater was authoritatively described by geologists to be the remnant of a volcano. Eugene Shoemaker, the geologist who first presented conclusive scientific data to bolster the impact explanation, was ignored or ridiculed by other scientists.

The first person to suggest Meteor Crater was caused by a meteor strike was mining engineer Daniel M. Barringer in 1901. He proposed mining the crater because he thought there was a giant iron meteorite buried in the middle. People said he was crazy.

PLANTING AN ION engine on an asteroid is not an ultimate answer, but I propose it as one hundred times more doable than any gravity tractor (GT). People forget—you need to get the mass to the asteroid. The GT seems simple but will be shown to be ineffectual. We can say that the GT can work over decades or centuries. But human programs aren’t likely over very long time spans. If you could move a large mass to the asteroid, instead of using braking rockets, your best chance is just to smack into it.

Current problems regarding landing on or moving an asteroid seem to be concentrated in two areas: First—composition. Asteroids can vary from a stellar core to a ball of loose, dirty snow. Second—close orbital mechanics.

Although cometary outgassing presents special problems, no matter how strange a rock spinning in space may look, it always has a spin axis with simple rotation. (I can devise a spinning rock that can’t be landed on, but I don’t believe they actually exist.) Landing on an axis (pole) is presumed simple.

Targeting a feature and landing on it is a problem that many missiles and bombs have shown has been solved. It is not complicated.

Then there is the nuke problem. I am not one who believes nuking an asteroid could be detrimental to Earthlings. But

Today it is difficult to believe that it wasn't very long ago at all that scientists said the craters on the moon were also volcanic in origin.

When S-L9 struck Jupiter in July 1994, just a single one of the many pieces produced a fireball nearly 9,000 miles in diameter. If Jupiter weren't sweeping large asteroids out of the solar system on the way to the inner planets, the Earth would have been hit many more times by large objects. Some estimates are that if Jupiter disappeared there would be a tenfold increase in large asteroid impacts on Earth.

Because just one part of one asteroid strike on Jupiter produced a fireball larger than the entire planet Earth, had it missed Jupiter and hit Earth, it would have wiped out most if not all life, an ELE or Extinction Level Event—something a species only sees once.

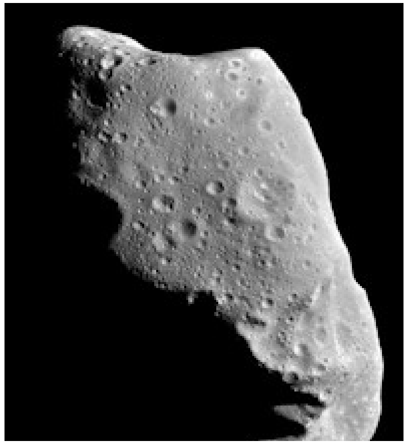
There were about a dozen similar size S-L9 fragments.

Asteroids, Sizing up the Threat

Just how dangerous are NEOs? You can see an estimate of the damage produced in various theoretical events for yourself. To generate a scientific prediction of the damage from various threat scenarios, just plug in the basic information at the Earth Impact Effects website to see the sort of impact different asteroids would have depending on their size, velocity, and where they hit.

Ceres is more than 600 miles in diameter (nearly 1,000 km) and would trigger quite an event if it struck Earth, although no one would be around long enough to write about the event. A Ceres strike would be classified as an ELE but don't worry, it won't happen.

Unfortunately even a strike from a much, much smaller asteroid (243 Ida, below) would be devastating. Scientists normally describe how dangerous an asteroid strike



would be based on the damage it would inflict if it hit a major city. From that standpoint a minor body could kill millions but the damage would at least be local.

The destruction of a major city would be a major disaster; however, that isn't the only possibility. An asteroid could strike the ocean triggering a massive tsunami capable of destroying entire coastlines. That has been shown in disaster movies.

If it hit the Three Gorges Dam, it would drown 10 million Chinese. If it hit Central Park, the mayor wouldn't have to worry about subway flooding any

this needs more sober study.

Planting ion thrusters is one of the better ideas. I would like to add my own recipe.

Sometime in the next decade, a really big rock will be determined to be a hazard. We will then wish we'd had the foresight to already have a spacecraft in Mars or Venus Lagrangian orbit to send ion engine "darts" to steer the rock out of the way. It might also have an optional nuke in its quiver. As a last resort, the spacecraft can be used as an impactor.

While waiting for this task, the orbiting spacecraft could be put to good use mapping and measuring star systems, exoplanet hunting, communications, and asteroid mapping and searching. etc.

So the bet is that it is worth putting numbers of spacecraft in distant orbit just to take advantage of the orbital position and readiness, if and when the need occurs. This type of "insurance mission" needs discussion.

—Eric M. Jones

more.

A modest sized NEO could also hit the desert area of Saudi Arabia, causing half the world's oil supply to be vaporized or the underground geology to be destroyed, making it impossible to pump the oil. It could hit central Pennsylvania and disrupt the entire Barnett Gas Field from New York to Ohio.

But much worse targets are every bit as likely to be hit.

For example, if even a tiny asteroid hit Yellowstone National Park, it could trigger the eruption of the giant and growing Yellowstone caldera creating a super volcano which would, at a minimum, probably end most life in the northern hemisphere.

What if a small asteroid hit a key point on the San Andreas fault near Los Angeles, or Hanford Washington (site of the most dangerous nuclear facility in the world)?

The Scale of the Threat

There are two widely used scales which quantify the likely damage caused by various NEOs striking the Earth—the Torino and Palermo Scales.

The Torino Scale is intended to give the public a general idea of the total threat from an object. That is, it includes both the likelihood of impact and the potential for damage if it does strike Earth. This is less precise, ranging from 0 to 10 with associated colors ranging from white (0 and safe) to red (8,9, and 10, certain collisions).

By contrast, the Palermo Scale is continuous and logarithmic, similar to the Richter earthquake scale. It is more useful in determining the actual level of threat posed by the smaller objects.

The Palermo Scale combines probability of impact and the kinetic energy of the object (mass and velocity) and rates them in relation to what is considered the background threat from random objects. A Palermo rating of "0" indicates an average threat, while a rating between "0" and "-2" indicates an object which should be monitored. A rank of "2" means an object poses a 100 times greater threat than a random asteroid.

So NEOs are dangerous. What can we do?

First we need to locate all threatening NEOs. This is much more difficult than you might think. Not only are there millions of them spread across the solar system, their orbits change all the time because they interact with other bodies to such an extent that it is sometimes impossible to determine if an observed NEO has already been cataloged.

Found it, Now What?

OK, say we have located and are tracking all the NEOs which are large enough to be dangerous and with orbits that pose a credible threat to the Earth, what can we do about them?

There are three options.

First, move the Earth out of the way. Probably impractical unless E.E. “Doc” Smith’s Lensmen or Heinlein’s “Slipstick” Libby are in charge of the project.

Second, destroy the object, aka the nuclear option. This is more practical, but only barely. Sending Bruce Willis or some other imaginary team of space demolition experts to the object is just within the realm of possibility. But what do they do when they get there?

Skipping over all the practical considerations up to the point of planting the explosives, what do we want to do with the object? Remember that only fairly large NEOs are of any real concern. Given a rock which would barely fit in a football stadium, and likely pretty dense, the team might aim to pulverize the rock or break it into small pieces.

For various reasons, turning it into sand is impractical. Anything less is most likely to just break it into two pieces, unless a lot of research is done first. Merely firing a rocket at the object is not the solution. The chances of a nuclear explosion hitting the right part of an asteroid with enough power and the composition of the object being exactly right to break into tiny pieces is very problematic.

Multiple simultaneous nuclear explosions are more a myth than a practical plan. Either the radiation from the first explosion would disrupt the other devices, or the shock wave (yes, there are shock waves in space) would destroy them, or they would be close enough to simply be blasted apart by the initial explosion.

Blowing up a NEO would be useful if you had time to determine the exact composition of the body and mine out a location to place a bomb near the middle.

Some scoff at this idea saying it would only break up the body into smaller ones all still on the way to Earth, but that ignores two critical points. Small objects will safely burn up in the atmosphere. A blast breaking apart an asteroid would throw most of the objects away from the Earth and accelerate those remaining on that path so they would miss. Therefore, blowing a threatening asteroid apart could make sense.

The third option is to alter the orbit of the object. This is surprisingly practical given enough lead time because it only takes a tiny nudge to alter the orbit by a few thousand miles 20 years later, or either speed up or slow it down by just a few minutes, or both.

Halling Asteroids

An obscure scientific oddity, the Hall effect, named for the discoverer, Edwin Hall in 1879, is the basis of a low thrust engine with no moving parts other than fuel, making it ideal for unattended use in space.

Hall thrusters are not a pipe dream. They are a product of cold war competition and both the U.S.S.R. and the U.S.A. developed working ion thrust engines in the 1950s. Hundreds are used in space vehicles (satellites) mostly for orbital corrections and a number are still operating.

These ion engines would be powered by solar panels.

Gridded Ion Thrusters

While the Soviet union focused on the development of Hall effect thrusters, the U.S. research was mostly on ion thrusters.

Solar Sublimation

The idea behind this deflection method is that 30 or so spacecraft carrying 30 meter mirrors could heat a spot on a threatening NEO to more than 2,000 degrees, enough to boil off the surface, not to reduce its mass, but so the NEO itself acts as fuel for its own jet.

Some, including myself, feel this is not practical since it involves so many space vehicles.

You could accomplish the same thing with a relatively small nuclear device which would boil off a large amount of the mass of an NEO acting as a jet. Near Earth collision it would be useless, but given a long lead time we only need to move the NEO a small amount or impart a small delta V using a small amount of thrust.

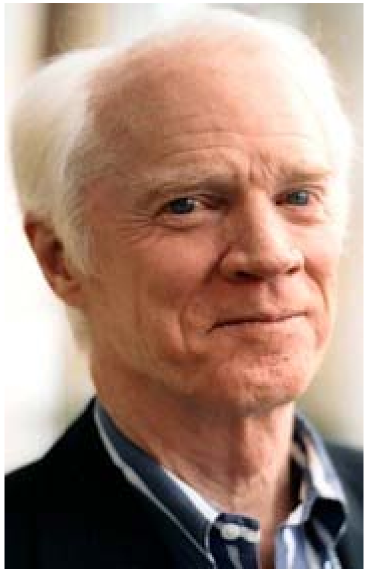
Tractor Field

It will surprise many to learn that there is already a totally practical tractor field which can attract objects. Quite simply, it is the gravitational field and only requires a large inert mass. But the operative word here is *large* because to alter the orbital path of a 100 kiloton or larger object, even when applied for a decade or more, a significant amount of mass is required. Colliding with the NEO is probably more practical.

Interview With Rusty Schweickart

In an exclusive interview with “Perihelion,” Russell L Schweickart (photo, below), Chairman Emeritus and co-founder of B612 Foundation provided some insight into how he got involved and what he and B612 see as possible solutions to the threat of NEOs.

If the name isn't quite familiar, he is also known as Rusty Schweickart, former Air Force fighter pilot and a member of the third class of NASA astronauts, pilot of the lunar module on the Apollo 9 mission. He was also the person who first tested the space suits used on the moon. Rusty spent a total of 241 hours in space and one hour eight minutes in EVA testing the "Portable Life Support System."



The B612 Foundation's current task is to raise about $400 million to launch their Sentinel satellite, an Earth orbit synthetic aperture radar satellite, into a solar orbit at the approximate distance of Venus.

There are other groups pursuing the same goal, such as the Osservatorio Astronomico Sormano. (See below for an exclusive interview with one of their scientists.) Locating all of the millions of objects large enough to pose a threat is such an enormous job that hundreds of scientists and probably thousands of amateur astronomers are needed and are contributing to the effort.

Perihelion: Was there some particular event which triggered your interest in NEOs and led you to co-found the B612 Foundation?

Schweickart: Not really ... but everything has its roots. In October 2001, a group of us met knowing that more and more NEOs were being found and that it was only a matter of time before one was discovered with "our address on it." But no one was doing anything about them.

We ... asked and answered two critical questions. First, can anything be done [about the threat to Earth and humanity from an asteroid strike] with current technology? Yes. Second, can we do anything to bring about such a capability? We felt that we had to try. So, in response, we formed the B612 Foundation.

Perihelion: Is B612 getting sufficient cooperation from NASA and the government?

Schweickart: Sufficient for what? This question requires further discussion. At one end of the spectrum the entire issue of planetary defense should be handled by government(s). Security of the citizenry is and always has been a, if not *the*, prime responsibility of government. At the other end of the spectrum is the realpolitik of the incompatibility between extremely infrequent, if devastating, challenges and the two-, four-, eight-year election cycle.

At the reductionist level, NASA is supporting B612/Sentinel per a negotiated Space Act Agreement (SAA) providing required deep space communications (with no payment), and NEO orbit determination and impact prediction for the hundreds of thousands of new NEOs Sentinel will discover.

However, NASA, per se, is investing no money in Sentinel or any other discovery system adequate to meet the planetary defense early warning needs, and has done almost nothing at all validating or demonstrating deflection capability, despite more than a decade of urging, cajoling, and demanding by countless committees, task forces, and expert panels who have addressed planetary defense.

Perihelion: Is the Foundation working with other governments? (Buzz Aldrin specifically and many others outside government feel we should be cooperating with China and India.)

Schweickart: We [B612] are certainly open to this but there are substantial off-putting circumstances involved. ITAR being only one, but a very significant impediment.

Perihelion: ITAR, the International Trade in Arms Regulations, in other words, arms control, is affected by U.S. laws regulating the exchange of vital technology with other, potentially hostile governments which makes the possibility of sharing very complex. This despite the fact that we are using Russian space launch vehicles. What Rusty is referring to is not that B612 is banned from working with China, but that the legal complexities and costs involved in determining if a specific technology is non-military makes cooperation impractical.

Schweickart: What the Foundation needs [to help launch] Sentinel is money. But while we are open to government financial support, domestic or international, most government financial support comes with control strings attached. Nor have any governments, save the U.S. (and that very limited), spent any serious money on NEO discovery. Europe (ESA) is best positioned and most cooperative, and informed. No others (China, India, Japan, Russia) have shown any real interest or willingness to even participate in meetings, let alone funding.

Our operating assumption is that we will need to raise the money for Sentinel via private donations ... as is the case in most large civic projects of similar magnitude (a new hospital wing, a performing arts center, refurbishment/construction of a museum, etc.)

Perihelion: Did you see increased interest in the Foundation after the recent Russian *event of February, 2013, over Chelyabinsk?*

Schweickart: Yes. But this “interest” is not easy to convert into significant donations on the multi-million dollar scale. Incidental support via the website increased notably, but these are small in magnitude while nonetheless heartfelt and thoughtful.

Perihelion: Being a science fiction magazine, we always ask if you were influenced by the early writers and stories, especially those by Heinlein and Asimov?

Schweickart: Indeed I was, and still am. Read any good ones lately?

Perihelion: Yes, we try to publish some every month.

Perihelion: What do you see as the best bet for deflecting NEO’s? I see the gravity tractor idea as impractical unless mass is brought up from the moon, or an asteroid is captured and equipped for that purpose, perhaps after being mined. Both myself and our Contributing Editor feel placing an ion engine on the object is the only practical means of altering the orbit.

Schweickart: This requires much technical discussion to understand ... it is not, despite the natural tendency think of it that way, a matter of either/or. No one who seriously understands the issue of asteroid deflection (and there are *very few* such individuals) believes or proposes the gravity tractor as a primary means of asteroid deflection. Yet everyone who understands the issues also realizes that the gravity tractor is an essential component of *every* asteroid deflection. At issue here is the fact that there are two things to avoid: the planet, and associated keyholes (the planet, once removed). If you don’t understand gravitational keyholes, you don’t get this. And few do.

Perihelion: This refers to the extreme complexity of calculating orbits where a large number of bodies are involved, including random bodies such as new comets, and various stability patterns seen in orbital dynamics such as Lagrange points. Consider how long people worked on The Three Body Problem.

Schweickart: Again ... at first order ... deflection of asteroids requires two components—a “robust” deflection capability (e.g. kinetic impact or nuclear explosion), combined with a “precise,” albeit extremely modest, deflection trim capability. The first enables an imprecise but sufficient planet avoidance; the second is necessary to also assure the avoidance of the gravitational keyholes nearby the planet. This is a fundamental, and non-intuitive physics issue ... actually orbital mechanics issue (which most physicists are clueless about).

Perihelion: A “keyhole” is simply the window through which an object must pass to be on a collision course with the Earth (or some other target). If the NEO passes any place outside the “keyhole” which is a specific region of space and a specific time, the *orbit will miss the planet. For example, the keyhole for the asteroid Apophis is about 400 meters (not kilometers) in width at a specific time in 2029. If the body passes through the keyhole we must try to deflect it, otherwise it will hit the earth April 13, 2036, Easter Sunday. The more lead time, the smaller the keyhole and hence the lesser amount of delta V which must be applied to move the body out of the collision course.*

Schweickart: Placing an ion (more generally an electric) engine on a NEO is *not* a simple, or even good idea. Again, lots of reasons, but the most obvious are: the object is spinning or tumbling; and *no one* knows how to anchor to a “rubble pile,” which most NEOs probably are.

Perihelion: What do you feel about leaving near Earth exploration to private industry?

Schweickart: I think the more proper adjective is not “near Earth” but “well understood.” We certainly understand venturing to near Earth space ... and turning that over to private industry is an excellent idea ... and we seem to be getting there. But there are some big science issues which are more in the realm of the general public interest (think space weather research) where government investment is more appropriate. Deep space activity (i.e. solar orbit) is generally far more expensive and absent profit potential (at the moment, anyway) and therefore more appropriate for government/taxpayer investment. However, something like the B612 Sentinel IR telescope in a Venus-like solar orbit is certainly well-understood and not inappropriate for private initiative. Furthermore, B612’s “bill” for designing, launching, and operating the Sentinel telescope is on the order of 50 percent of what the government would have to pay were it doing the job. The primary “fly in the ointment” here is that the Sentinel “product” is not being sold to NASA, or the public ... it is being given freely to the world as a public safety service. Hence, we’re a non-profit corporation.

Again, elaboration on this is not inappropriate. Ultimately, for some rather subtle reasons, deflecting an asteroid may well be most effective if performed by a private, for profit entity. Most appropriately *after* demonstration of the technology by the government(s). One would certainly be justified in arguing that this is “in the public interest!” Lack of evidence to date notwithstanding!

Perihelion: Regarding the ion engine. If we have the technology to place one or more on a body, we should be able to use several to control spin or tumble since that is what they are used for now. Of course the Delta-V both ways will be a problem if we have to send men to the object to work on the surface. (NASA landed the NEAR Shoemaker probe on Eros more than a decade ago and it survived the landing well enough to continue transmitting.)

Schweickart: What you propose is *very* complicated! Attaching a single propulsion system to an asteroid is a monumental robotic task ... and we have *no clue* how to attach to an asteroid. Think dry powdered snow ... *not* a consolidated soil or regolith [dust, soil, gravel, etc., overlying a solid ground] ... these things are extremely porous and unconsolidated. Let alone [embedding] several. It would be orders of magnitude more costly than to simply collide with the asteroid ... i.e., kinetic impact. This is *not* likely to break up the asteroid, although that is not known for certainty. Our [B612] policy and practice is very pragmatic; we are *only* interested in what is available with current technology. Lots of things may be available at some time, but we consider only existing technology. This is public safety, not some future potential.

Both kinetic impact and gravity tractor work independent of whether the asteroid is a single consolidated body (only the smaller ones, those <~100 meters diameter, are thought to be consolidated bodies ... and even they have specific gravities ~2.0–3.0 ... therefore lots of pore space).

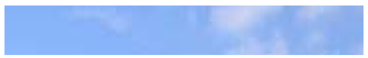
Perihelion: Wouldn't rubble objects be the only ones appropriate for a nuclear device? Obviously, you don't want to just break up a solid one into two pieces so there is a greater chance of hitting a city.

Schweickart: That's part of the complexity. We do not, generally, consider nuclear surface or sub-surface bursts. The favored flavor is a "stand-off nuclear explosion" at something like one asteroid radius, which instantaneously vaporizes the surface on that side (there is no blast effect ... it's all neutron heating) pushing the asteroid in the opposite direction. The point is you don't slow down to rendezvous with it. You nuke it as you fly by on a close pass. More recently some of the nuke guys have been leaning toward the macho mode of blowing it up in the literal sense. Run directly into it with a slightly delayed explosion. Fragment it on purpose. They don't seem to realize that they will forever be responsible for a man-made annual meteor shower comprised of asteroid fragments of uncertain size, essentially forever. The standoff technique would (they say) work, rubble pile or no.

Our (B612) general take on use of nukes is *don't do it* unless there is no alternative. Nukes should only be used as a last resort. This is also the yet-to-be-formalized position of the UN/COPUOS, as well. No one, especially non-U.S. nations, want to see nukes used in space ... *for anything*. Especially if it's the U.S. doing the using. International trust, public trust, in the process, is very critical. Using nukes flies directly in the face of this necessity.

Interview With Francesco Manca

Francesco Manca is a foremost Italian astronomer at the Sormano Astronomical Observatory in Sormano, Italy (below) with observational experience on the research of Near Earth Objects. His professional activity concerns the application of measuring systems encoders installed on telescopes and radio telescopes such as the VLT, LBT and ALMA (Atacama



Large Millimeter Array). The asteroid 15460 Manca is named in his honor.

Sormano is a privately funded observatory 40 km north of Milan at about 1,000 km altitude. The main instrument is a f/6.5 Ritchey-Chrétien Astrograph with a 20-inch primary and a 6-inch guide scope. The Sormano Observatory is at the forefront of moderate sized private efforts adding to our knowledge of NEOs.

Perihelion: You appear to have four major activities. First, educating the public. Second, discovering NEOs. And third, assisting in development of orbital analysis software and orbital analysis of any objects. Is this correct and do you place special emphasis on any one of those?

Manca: Our first activity, begun in 1989, which has thus far observed 4,179 total objects, is the Near Earth Objects follow up, confirming already discovered objects. Secondly we work to discover new minor planets from Sormano, calculate orbits and help with the identification of each object. Finally, we work to educate the public.

Perihelion: I see that about 100 numbered and about 30 unnumbered NEO discoveries have been credited to Sormano. Were they all found using the 20-inch scope?

Manca: Yes, all minor planets discovered by our scientific activity are presented on our web site. These were discovered from Sormano using the old 20-inch telescope, which was later replaced to improve performance and obtain better images of comets and deep space objects.

Perihelion: Many objects are discovered, then lost, and discovered again. Obtaining accurate orbits is critical to maintaining an accurate database and I see you are responsible for many of the computations identifying objects. Did you use the OrbFit software?

Manca: We use custom software developed at Sormano by Augusto Testa. He is also responsible for updating our internal database. Starting with this accurate database (we have all observations and orbits published by the Minor Planet Center), we compute new accurate orbits in order to maintain priority lists of objects to be monitored in the future for their minimum orbit intersection distance and close encounters.

Our staff and observatory focuses on many years of follow up activity of near Earth asteroid orbit computations to identify them and calculate their close approaches to the Earth and inner planets.

In addition, we also use OrbFit software to calculate the non-linear error in reference to the close approaches of dangerous asteroids, and to check close encounters to find these objects on old astronomical photographs and improve the accuracy of their orbits.

Perihelion: Do your computations include the determination of so-called gravitational keyholes?

Manca: The so-called keyholes are not reported by us because [they are a critical calculation] and [not an] easy computation as, for example, the case of the PHA asteroid (99942) Apophis. This object passed a keyhole in 2013. Keyholes are very important to understanding future close approaches to Earth.

John McCormick is a trained physicist, science/technology journalist, and widely-published author with more than 17,000 bylines to his credit. He is a member of The National Press Club and the AAAS. His full bibliography can be accessed online.