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Ceres Polar Wander *by Alan Fischer, Pamela Gay, and Chris Holmberg*

Not all poles that wander are lost.* In the case of Ceres' rotational axis, detailed measurements made by the Dawn mission allow the wandering nature of its pole to be found. A new paper by PSI Senior Scientist Pasquale Tricarico documents three lines of evidence that all point toward this dwarf planet's pole moving 36 degrees relative to the landscape of Ceres.

Pasquale's paper, "True polar wander of Ceres due to heterogeneous crustal density," appeared in *Nature Geoscience* last October and was a featured article on the cover.

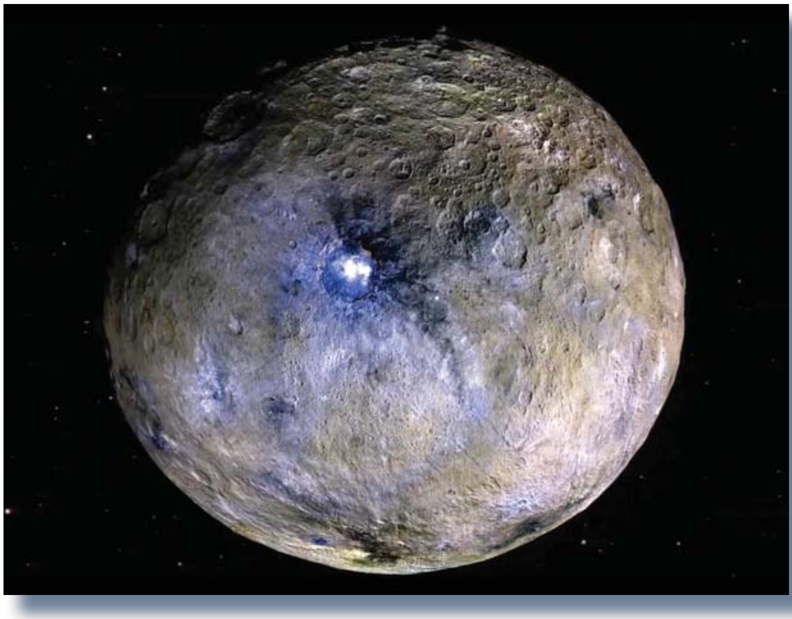
The evidence of this polar wander, or reorientation, can be mapped through measurements of Ceres' gravitational field, by tracing features such as ridges that tend to arise along the equator, and by looking at surface features such as cracks and faults that align relative to a planet's rotation.

As the Dawn mission flew above the surface of Ceres, differences in the dwarf planet's internal structure tugged on the spacecraft in measurable ways. Using a technique originally published in 2013, Pasquale took advantage of these gravity measurements to map the density of Ceres' surface layer, or crust. While it is generally expected that the thickness and density of the crust will vary from thicker at the equator to thinner at the pole, Pasquale found that Ceres varies oddly, with equatorial density anomalies that could have triggered the reorientation of Ceres, causing the paleo, or old, equatorial region to sweep north and south of the current equator on either side of the planet.

The Nature Geoscience issue with Pasquale Tricarico's paper on Ceres polar wander featured on the cover.

Reprinted by permission from Springer Nature: Nature Geoscience, "True polar wander of Ceres due to heterogeneous crustal density," by Tricarico, P. Copyright 2018

Further analysis presented in Pasquale's paper looks at surface features on Ceres, such as ridges, and finds the topography also consistent with the same paleo equator. To get from this historic, paleo orientation to the orientation we see today, Ceres' pole must have moved, and this process would have left its own marks on the dwarf planet's surface.



In this view of dwarf planet Ceres the current north rotational pole, near the top of the image, has moved 36° from its old position.

Credit: NASA/JPL-Caltech/UCLA/MPS/DLA/IDA

Flattened worlds like Ceres, referred to as oblate spheroids, experience a variety of internal stresses when their poles migrate. Regions migrating towards the equator may form normal faults where the crust pulls apart and one side of the fault drops down relative to the other. Regions migrating toward the pole will experience compressional stresses that can produce thrust faults, where one side rises up compared to the other. Examination of Dawn's detailed maps showed clear evidence of these kinds of features, and actually allowed Pasquale to trace out the meandering path of Ceres' pole as it wandered relative to Ceres' surface. The wandering nature of this change indicates that the pole migration wasn't a straightforward or sudden process. Rather, it appears

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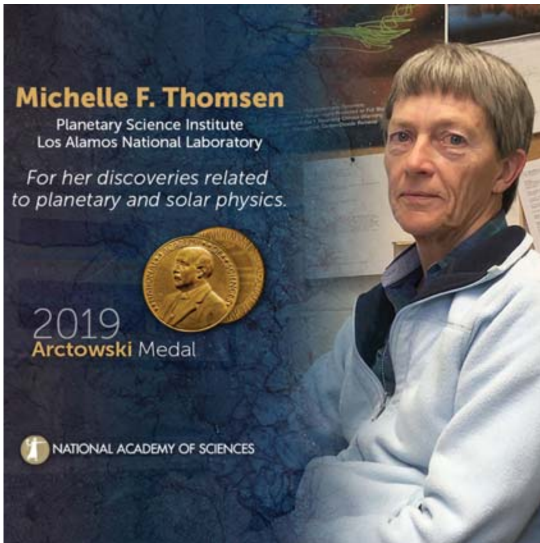
Inside this issue:

PSI's Michelle Thomsen Named 2019 Arctowski Medal Recipient *by Alan Fischer*

In January the National Academy of Sciences announced PSI Senior Scientist Michelle Thomsen will receive the 2019 Arctowski Medal for her outstanding contributions to the study of solar physics and solar terrestrial relationships. She will receive a bronze medal, a $100,000 prize, and $100,000 to support research in solar physics and solar terrestrial relationships at an institution of her choice.



Michelle is receiving the Arctowski Medal in recognition of her "fundamental contributions to our understanding of the relationships between the Sun and its planetary bodies, with a particular emphasis on the physics of collisionless shocks and the dynamics of the planetary magnetospheres of Earth, Jupiter, and Saturn," the Academy said.

"I feel very humbled and grateful to the colleagues who nominated me, that they would consider me a suitable candidate. I am also grateful for all the wonderful research opportunities I have had, getting to work with data from amazing space missions and with a host of talented colleagues," Michelle said. "I find it particularly pleasing that the selection recognizes that 'solar-terrestrial relationships' embraces other planetary magnetospheres as well as the Earth's, providing an even richer set of phenomena to explore."

Michelle said the upper atmosphere of the Sun, known as the corona, is extremely hot and expands continuously outward into the Solar System, forming the solar wind, a very fast-flowing gas of charged particles – plasma – carrying magnetic fields generated at the Sun. When the solar wind encounters the Earth or other magnetized planets like Mercury, Jupiter, and Saturn, a bow shock forms upstream from the planet to slow and deflect the flow around the planetary obstacle. The shocked solar wind flows around but also interacts with planetary magnetospheres to drive a fascinating set of magnetospheric processes, including aurora, trapped radiation belts, and plasma heating and loss. "I have had the good fortune to study the nature of the bow shock and how it does its job of slowing and deflecting the solar wind. I have also been able to help explore the effect of solar wind variability on magnetospheric populations and processes from the vantage point of satellites in geosynchronous orbit around the Earth," she said. "I have had the opportunity to investigate similar magnetospheric processes at Jupiter and especially at Saturn, with data from the Cassini spacecraft. Our studies of the outer planets have shown us that while the physics is universal, the relative importance of various physical processes varies a lot depending on the particular properties of any given planetary body, such as size, strength of the magnetic field, rotation rate, and the presence of plasma sources within the magnetospheres, such as moons."

Michelle's pioneering work continues today as a member of the teams studying the influence of solar wind on the magnetospheres of Jupiter and Saturn. "I will continue to study planetary magnetospheres and how they interact with the variable solar wind. I am actually hopeful that the award will benefit other people's work, especially the next generation of space scientists," Michelle said.

The Arctowski Medal will be presented to Michelle at a ceremony on April 28, during the Academy's 156th annual meeting in Washington, D.C.

The Arctowski Medal was established in 1958 at the bequest of Jane Arctowska in honor of her husband, Henryk Arctowski.

Ceres Polar Wander *(Continued from front page)*

that the process occurred over time and may have been complicated by the center of Ceres rotating somewhat separately from its crust.

"The most surprising aspect of this paper to me is the observation that the pole of Ceres must have followed an indirect path to its current pole," Pasquale said. "If crust and mantle are allowed to shift with respect to one another that could point to a layer of reduced friction between crust and mantle and one of the possible mechanisms to reduce friction could be an ancient water ocean beneath the crust."

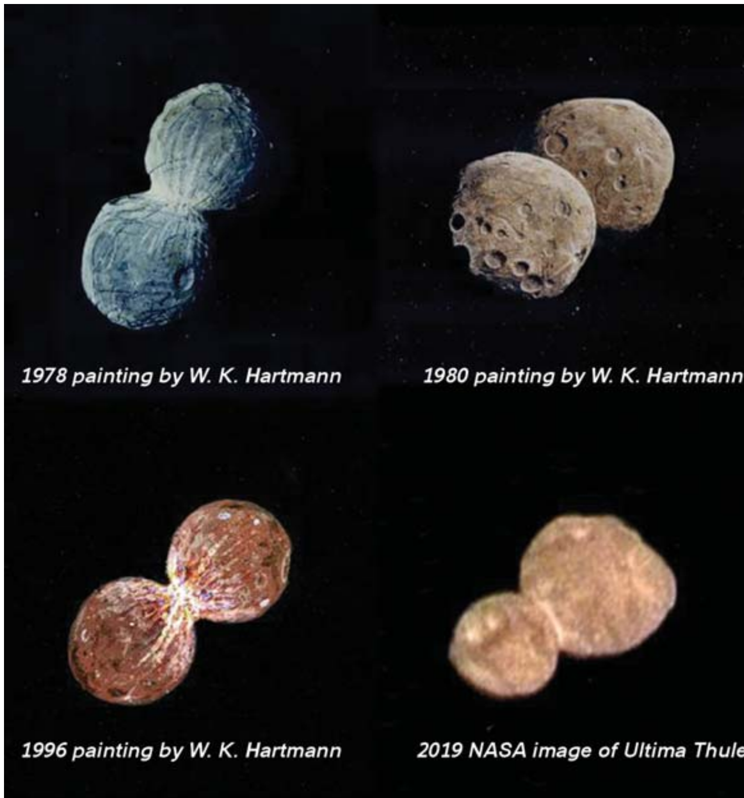
The Dawn mission has orbited Ceres for more than three years, gathering very detailed observations and allowing the construction of detailed geophysical models. These detailed models can then be adapted for comparison to other icy bodies, Pasquale said. One such example is the parallel between the well-known equatorial ridge of Saturn's moon, Iapetus, and the remnants of the paleo-equatorial ridge of Ceres.

**Apologies to J.R.R. Tolkien for the creative misquote of, "Not all those who wander are lost," from The Fellowship of the Ring.*

Pasquale's research was funded by grants to PSI from NASA's Dawn at Vesta Participating Scientist and Dawn at Ceres Guest Investigator pro-

PSI Scientist William K. Hartmann Anticipated "Snowman" Asteroid Appearance *by Alan Fischer*

While the world is agog at the so-called "Snowman" shape of the most distant visited asteroid, revealed on Jan. 2, 2019, by the New Horizons spacecraft, the concept is nothing new to Tucson scientists, including many PSI researchers. PSI Senior Scientist Emeritus, William "Bill" K. Hartmann, made a number of paintings from 1978 to 1996 to illustrate such bodies. The first three images at right are paintings by Bill, and the lower right image shows the first released color photo sent back from New Horizons. The story goes back to the late 1960s.



Decades before recent NASA spacecraft photographed the most distant visited asteroid Ultima Thule up close, PSI Senior Scientist William K. Hartmann was painting what he reasoned contact binary asteroids might look like. The similarity is unmistakeable. *(Credit: NASA/APL/SWRI)*

In 1969, University of Arizona astronomers at the Lunar and Planetary Lab (LPL), Larry Dunlap and Tom Gehrels, noticed that asteroid 624 Hektor, far beyond the main asteroid belt in the region of Jupiter, showed extreme changes in brightness as it rotated. The broadside view was as much as 3.1 times brighter than the end view, suggesting a very elongated object.

In 1971, astronomer A. F. Cook argued that Hektor might be a binary asteroid (an asteroid and its satellite closely co-orbiting or touching one another). However, two spheres of the same material could produce a light variation of no more than two to one.

Observations started by Bill's fellow UA graduate student, Dale Cruikshank, and later by Bill and Dale observing together at 14,000-ft. Mauna Kea Observatory in the 1970s, proved that the brightness change was not caused by one side having brighter materials, but rather by an unusual elongated shape. Bill theorized such bodies might have formed in the primordial Solar System by low-velocity collisions of asteroidal bodies, from which the planets were growing. Such bodies welded together by collision were called contact binary asteroids – "binary" meaning two bodies and "contact" indicating they were touching each other instead of orbiting around each other.

In 1980, PSI Senior Scientist Stu Weidenschilling published a paper on how the two halves of a contact binary might have their shapes distorted, depending on their bulk strengths and the rotation rate of the object. In the 1980s, PSI Senior Scientist Faith Vilas, and, independently, Dale and Bill too, added evidence that elongated shapes might be more common among outer Solar System asteroids than in the main asteroid belt.

Bill's 1978 painting portrayed the initial contact binary asteroid concept of Hektor with grey colors as found on the Moon. "My astronomical paintings," he says, "are not just flights of fancy, but a serious attempt to make something both beautiful and realistic out of what we humans have learned about other worlds." By 1980, Dale and Bill had shown that many bodies in the outermost Solar System had a dark, reddish brown color, and his 1980 and 1996 paintings added Bill's estimate of how this color might look.

In the first days of 2019, New Horizons returned the first photos from the most distant world yet visited by our space probes. It was not only the first obvious image of a contact binary structure, but also looked strikingly like Bill's 1996 visualization from 22 years ago. Bill happily notes that his 1978 and 1996 paintings show bright material in the "contact zone" where the two bodies collided as seen on the Moon, and sure enough, the New Horizon spacecraft photo also shows bright material there. "We live in an era where scientific findings are being criticized," says Bill, "but if we can predict phenomena we see on other worlds, we must know something about what we are doing!"

PSI Research Scientist Isaac Smith commented: "It's very cool to see that the initial work from decades ago is supported by this month's findings. I am frequently impressed by the accurate insight of scientists who worked with much lower resolution than we have now."

Front page banner: *A picture from the High Resolution Imaging Science Experiment (HiRISE) on NASA's Mars Reconnaissance Orbiter shows the area of Acidalia Planitia where the fictional Ares 3 mission landed in the novel, and later in the Hollywood film, "The Martian." (Credit: NASA/JPL-Caltech/Univ. of Arizona)*

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Chris Holmberg, Editor and Writer
Alan Fischer, Writer and Photographer

Special thanks to Dianne Janis, Carol Neese, and Elaine Owens.

Snowflakes and Planetesimals in Tucson

by William K. Hartmann, Senior Scientist Emeritus

On February 22, 2019, Tucson had one of its rare (once every year or two) snowfalls. It was unusual not only for the snow, but for the snowflakes themselves. At several periods during the storm, the "flakes" coming down were actually flattish aggregations of flakes, as much as an inch wide, slowly wafting out of the sky.

Being one of the nerdy subclass called planetary scientists, I got to thinking that here we were seeing an example related to the formation of planets! There has long been evidence from meteorites, supported by observations of newly formed stars and by theory, that the newly formed Sun was surrounded by a disk-shaped "solar nebula" of gas and dust. As it cooled, bits of solid matter condensed from the gaseous material, just as raindrops and hailstones condense in Earth's atmosphere.

There's always been the problem, however, of how these tiny grains began to accumulate into larger aggregates on the way to forming so-called "planetesimals," asteroid-sized bodies, and eventually planets. In the case of the solar nebula, it's thought that electrostatic forces may have been involved. In fact, I published some early PSI experimental papers in the late 1970s about how bodies with dusty, granular surfaces tend to absorb impactors during low-speed collisions, rather than allowing the impactors to bounce off.

But here in front of our eyes were examples of three millimeter snowflakes aggregating – somewhere up in our nebular atmosphere – into 25 millimeter-wide aggregates! I ran outside and took some photos, looking up almost vertically to the sky (image above), into distant atmospheric space, showing these "snow-planetesimals" drifting through the atmosphere.

2019 Pierazzo International Student Travel Award Winners

by Alan Fischer

The winners of the 2019 Pierazzo International Student Travel Award, established by the Planetary Science Institute, were selected in January.

The Pierazzo International Student Travel Award was established by PSI in memory of Senior Scientist Betty Pierazzo to support and encourage graduate students to build international collaborations and relationships in planetary science.

Katherina Feng

Ying "Katherina" Feng of the University of California, Santa Cruz, will receive the award for a U.S.-based graduate student traveling to a planetary meeting outside the U.S. Her research title is "Probing the Phase Dependence of Atmospheric Inference for Hot Jupiters" and in August she will be attending the Exoclimes V conference at Oxford, in the United Kingdom.

Sammy Griffin

Sammy Griffin of the University of Glasgow, Scotland, received the award for a non-U.S.-based graduate traveling to a planetary meeting within the U.S. Her research title is "New Insights into the Magmatic and Shock History of the Naklite Meteorites from Electron Backscatter Diffraction." In March 2019 she attended the 50^{th} Lunar and Planetary Science Conference in Houston.

Each awardee will be presented with a certificate and a check for $2,000 at their respective conferences.

Betty Pierazzo (1963-2011) was an expert in the area of impact modeling throughout the Solar System, as well as an expert on the astrobiological and environmental effects of impacts on Earth and Mars. In addition to her research, she was passionate about education, teaching and public outreach, developing planetary-related classroom materials, professional development workshops for teachers, and teaching college-level classes. Betty believed in the strength of broad collaborations in all of her research and education activities.

This award memorializes the scope of how she lived her life and the good she sought to bring to our profession and communities.

To contribute to the Betty Pierazzo Memorial fund, please go to: http://www.psi.edu/support/pierazzofund

Director's Note

The New Year has not been without drama! The government shutdown shuttered NASA for a month. Some other organizations had to shut down as a consequence. Fortunately, we still had access to our grant funds and invoices continued to be paid on contracts. We had also prepared, ensuring we had other resources available in the event our regular funds started drying up. By the end of the shutdown, everyone at the Institute was still whole. There were some disruptions to program and new mission schedules, but this is being worked out as NASA continues to bring things back on track.

More recently, there was some very positive financial news for the Institute. Every year, for more than twelve years, when PSI negotiated its annual indirect cost (overhead) rates with the government, we have been given provisional and not final rates. The agency doing the negotiation for NASA could not do the audits necessary to award final rates. The Sword of Damocles hanging over our heads was if we were systematically and wrongly charging anything to overhead, we would have to pay the amount accumulated over more than a decade back to the government out of unrestricted funds. If it was a large amount, we could be in trouble. When the audit was completed, the government found not a single error on our part. This was a stunning result and a credit to our financial operations.

It is also a pleasure to congratulate our scientists who have been recognized for their contributions to our science and community. Michelle Thomsen received the Arctowski Medal for her work on magnetospheres described elsewhere in this Newsletter. She is a leading figure in studies of the plasma composition and flow dynamics within the magnetospheres of Saturn, Jupiter and Earth. Plasma physics is, in my book, very challenging, and I have heard colleagues say they fear to tread in some of the areas she has taken on.

Faith Vilas received the Masursky Award from the Division for Planetary Sciences of the American Astronomical Society. It is well deserved. I was there when, in the midst of the 9/11 attack and the collapse of the Dawn site visit, Faith shut the down the Discovery selection process, preserving its integrity and allowing her to restart it a month later. The Dawn mission to Vesta and Ceres might never have flown, but for her quick action. This was just one of many accomplishments for which she was recognized with this award.

I would also like to laud an athletic accomplishment of one of our scientists. Ryan Watkins recently outperformed over 20 other members of the Institute in accumulating the most steps in two days. She was eight months pregnant at the time.

We have a lot of inspirational people!

Mark V. Sykes
April 2019

PSI Staff News

Last October at the 50th American Astronomical Society Division for Planetary Sciences (DPS) meeting in Knoxville, the 2018 Harold Masursky Award for meritorious service to planetary science was presented to PSI Senior Scientist **Faith Vilas**.

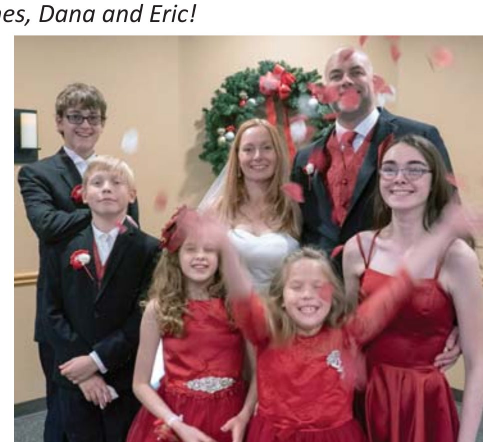
PSI scientist Faith Vilas (right) accepted the Harold Masursky award from Cathy Olkin, Chair of the DPS.
Credit: Henry Throop

In doing so, AAS acknowledged her many contributions: At a time of national duress following the chaos of the 9/11 attack, she insured the integrity of the Discovery program selection process; as the first Chair of the NASA Small Bodies Assessment Group, she established its operational practices and made it the viable entity that continues today; as Chair of the DPS, Faith played a key role in establishing the Carl Sagan Medal, which was the first major statement in support of the importance of communicating our science with the public. She has mentored and inspired young people who have become well-known figures in our profession, and others who have taken an appreciation of our science into other careers. She has served on many academy and NASA panels. Her service to the field and to society has been exemplary.

Brava, Faith!

In December 2018, PSI Research Scientist **Eric Palmer** and Dana Norton were married in Tucson. The new family happily blends Dana's two children and Eric's three.

Best wishes, Dana and Eric!



The wedding party, from left: Thomas Palmer, Val Norton, Anna Palmer, Dana Norton, Karina Norton, Eric Palmer, and Jenna Palmer.
Credit: David Heisley

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Mapping Potential Water on Mars *by Alan Fischer*

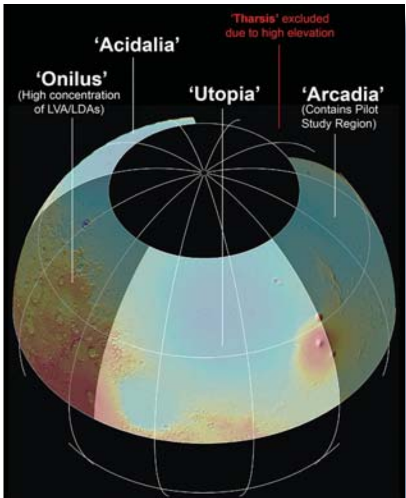
Missions carrying humans to Mars will require on-site resources, and a project led by PSI scientists Nathaniel "Than" Putzig and Gareth Morgan is mapping the availability of potential shallow water-ice sources across the surface of the Red Planet.

Two teams led by Than and Gareth were contracted by NASA to pursue separate mapping efforts of subsurface ice deposits in Arcadia Planitia. The teams were combined in a joint project called "Subsurface Water Ice Mapping (SWIM) on Mars," which extends the coverage of the mapping project from an experimental swath over Arcadia Planitia to all other low elevation regions across the Martian Northern Hemisphere.

"Water ice will be a critical resource for human explorers on Mars, not only for life support but also for generating fuel to power equipment on the ground and rockets for the return journey to Earth," said Than, a Senior Scientist at PSI. "Maps that identify the availability of potential water will help determine where humanity will establish its first outposts on Mars."

The SWIM team is producing new maps of the likelihood of subsurface ice deposits over these regions by combining radar, thermal, neutron, altimetry, and image data from several Mars-orbiting spacecraft. The team is also employing newly developed techniques that include using radar returns to infer the presence of ice within the top 5 meters of the crust and applying advanced radar processing to improve resolution at depth and to estimate the purity of ice in the subsurface.

"The goal of the SWIM project is to provide a set of mapping products using existing spacecraft data that delineate subsurface ice in the mid-latitudes of Mars," said Gareth, a Research Scientist at PSI. "We aim to identify and map possible subsurface ice in each data set and use a combination of all data sets to assess the likelihood of ice being present in shallow and deep zones, above and below 5 meters in depth."



The Subsurface Water Ice Mapping project is currently studying large expanses of the northern hemisphere of Mars to identify potential shallow water-ice resources. Work is focused in the four outlined regions. *Credit: Gareth Morgan*

In addition to an expanded 'Arcadia' study region, the SWIM team has been contracted to map three other study regions. These are the 'Acidalia,' 'Onilus,' and 'Utopia' regions shown above. Results from each of these study regions will be integrated into a single northern hemisphere ice consistency map by the end of April 2019.