National Aeronautics and Space Administration

Cutting edge
Goddard's Emerging Technologies

The Fearsome Foursome

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in this issue:

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The Fearsome Foursome

Technologies Enable Ambitious MMS Mission

It was challenging developing a mission that could fly four identically equipped spacecraft in a tight formation and take measurements 100 times faster than any previous space mission — a feat enabled in part by four Goddard-developed technologies that in some cases took nearly 10 years to mature.

The four MMS observatories are processed for launch in a cleanroom at the Astrotech Space Operations facility in Titusville, Florida. The MMS mission launched March 12, 2015.

"To get to this point in time, we had to overcome a number of engineering challenges," said Brent Robertson, the deputy project manager of the Magnetospheric Multiscale (MMS) mission, which NASA launched aboard a United Launch Alliance Atlas V 421 rocket in early March. "These technologies and engineering efforts were necessary to allow MMS to meet its objective of understanding magnetic reconnection" — the fundamental, yet poorly understood process that MMS was specifically designed to study (see related story, page 16).

While reconnection occurs throughout the universe when magnetic field lines within plasma connect and disconnect, closer to home, it drives space weather that can disrupt low-Earth-orbiting spacecraft and lead to communications and power blackouts on Earth.

NASA has never before flown a mission dedicated exclusively to studying this phenomenon, let alone with four precisely aligned, spinning spacecraft, each roughly the size of Fenway Park when each of the satellite's eight booms fully deploy. "No one has done what we're going to do," said MMS Deputy Mission Systems Engineer Gary Davis.

During the mission's first phase, which begins in September, the spacecraft will zip through reconnection sites on the sun-side of Earth, where the orbit extends out toward the sun to around 47,500 miles. About one year later, ground controllers then will move the spacecraft to Earth's night-side or magnetotail where the magnetic fields also reconnect — an orbit that extends away from Earth to almost 99,000 miles, nearly halfway to the Moon.

Navigator and GEONS

However, science operations can't happen before the four move into a highly elliptical orbit and assume their pyramid-shape formation that places the spinning spacecraft just 6.2 miles apart. It required a breakthrough to accomplish this exacting formation and the Goddard-developed Navigator GPS provided the solution, Robertson said.

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About the Cover

Hundreds of Goddard employees and contractors spent 5 years simultaneously building the four spacecraft that make up NASA's Magnetospheric Multiscale (MMS) mission. Principal Investigator James Burch, of the Southwest Research Institute in San Antonio, Texas, serves as the science lead on this Goddard-led effort. Each of the four spacecraft is equipped with 25 sen¬sors and other components provided by more than 40 partner institutions in the U.S., Europe, and Japan. Pictured here are four Goddard technologists — Anne Long, Luke Winternitz, Penshu Yeh, and Adán Rodríguez-Arroyo — who are posed against an MMS launch shot. The four developed technologies that helped make this complex mission possible.

Photo Credits: Bill Hrybyk/NASA) and Aubrey Gemignani/NASA

Begun in the early 2000s as an enabling technology for MMS-type missions, the Navigator receiver and associated algorithms quickly acquire and track GPS radiowaves even in weak-signal areas well above the GPS constellation consisting of 30-plus satellites about 12,550 miles above Earth. In addition to tracking weak signals, the Navigator must operate as the four spacecraft spin at three revolutions per minute. As a result, each MMS satellite is equipped with two Navigator receivers (primary and redundant). Four antennas are placed around the perimeter of each, assuring contact with the tracked GPS satellites.

To the satisfaction of the technology's architect, Goddard technologist Luke Winternitz, the receivers have proven very robust. Shortly after the GPS receivers were powered on after the launch, Navigator became, at more than 43,000 miles above Earth's surface, the highest-ever operational GPS receiver in space. "We're tracking up to 12 GPS satellites at maximum altitude and track on average about nine," Winternitz said. "We're really excited about their performance so far."

Because the MMS spacecraft must maintain a precise formation, the mission also needed the ability to not only determine the immediate locations of the four observatories, but also predict where they would be in the future and how fast they would be traveling. Providing that predictive data is the Goddard Enhanced Onboard Navigation System (GEONS), created by Goddard technologist Russell Carpenter and his collaborator, Anne Long, a technologist with A.I. Solutions, a Lanham, Maryland-based contractor.

"Almost all activities associated with operating the mission depend on where the satellites will be positioned a few days hence," Long explained. That includes everything from determining the best time to downlink telemetry and scientific data to calculating when ground controllers would command the firing of the satellites' onboard thrusters, which move and help maintain their orbital formation — an exercise that will happen at least once every couple weeks. "You need to plan the formation in advance," she said.

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The CAVE, Color-Coding, and Cleanroom

Goddard Facilities and New Processes Enable MMS

The technological advances that helped make NASA's Magnetospheric Multiscale (MMS) mission possible weren't restricted to the four identically equipped spacecraft. They also included the use and development of new facilities and processes that helped planners accomplish something that had never been done before.

"The mission was unprecedented and required us to rethink our processes," said MMS Deputy Mission Systems Engineer Gary Davis. "We've never built four-of-a-kind spacecraft all at once."

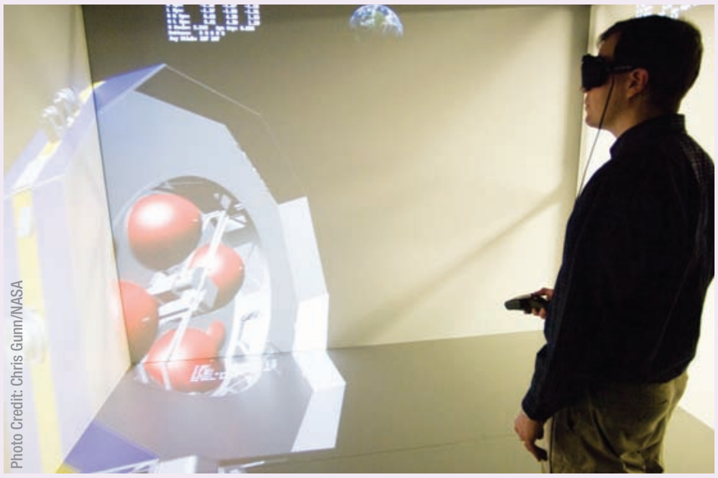

Photo Credit: Chris Gunn/NASA

When wearing special eyewear and carrying a wand to control visualizations, users actually can walk around the object they've created in Goddard's CAVE facility. Here, a technologist studied the stability of an early design of the MMS spacecraft.

The CAVE

Rethinking processes, however, began long before the team settled on a final spacecraft design. To better understand the dynamics of the spacecraft's body, the team used a visualization facility called the CAVE, which stands for Cave Automatic Virtual Environment.

This high-fidelity capability, created by Goddard aerospace engineer Dave Folta, visualizes 3D models developed in computer-aided design packages, projecting images onto three walls and the floor to create a fully immersive environment (*Tech Trends*, Spring 2009, Page 2). When wearing special eyewear and carrying a wand to control

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The 'CAPEd' Crusader

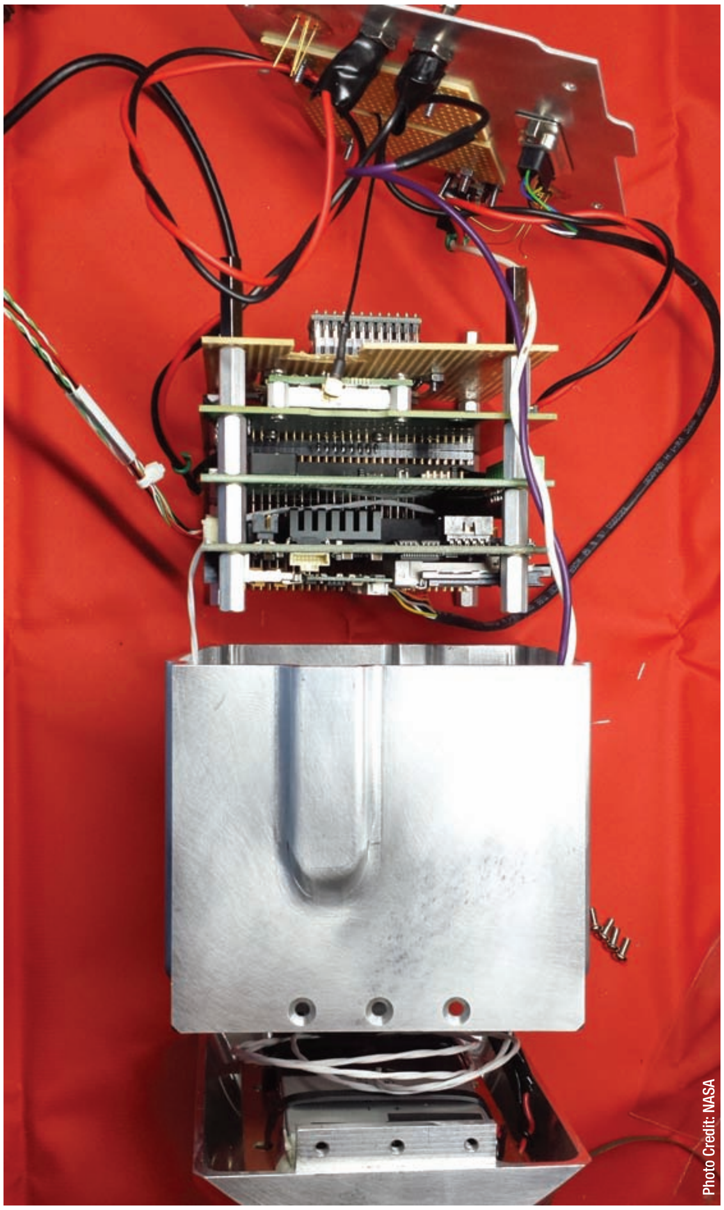
Goddard Technologist Advances CubeSat Concept for Planetary Exploration

Although scientists are increasingly using pint-size satellites sometimes no larger than a loaf of bread to gather data from low-Earth orbit, they have yet to apply the less-expensive small-satellite technology to observe physical phenomena far from terra firma.

Goddard technologist Jaime Esper, however, is advancing a CubeSat concept that would give scientists that capability.

Dubbed the CubeSat Application for Planetary Entry Missions (CAPE), the concept involves the development of two modules: a service module that would propel the spacecraft to its celestial target and a separate planetary entry probe that could survive a rapid dive through the atmosphere of an extraterrestrial planet, all while reliably transmitting scientific and engineering data.

Esper and his team are planning to test the stability of a prototype entry vehicle —the Micro-Reentry Capsule (MIRCA) — this summer during a high-altitude balloon mission from Fort Sumner, New Mexico.



Technologist Jaime Esper and his team are planning to test the stability of a prototype entry vehicle —the Micro-Reentry Capsule — this summer during a high-altitude balloon mission from Fort Sumner, New Mexico.

'Like No Other CubeSat Mission'

"The CAPE/MIRCA concept is like no other CubeSat mission," Esper said. "It goes the extra step in delivering a complete spacecraft for carrying out scientific investigations. We are the only researchers working on a concept like this."

Under his concept, the CAPE/MIRCA spacecraft, including the service module and entry probe, would weigh less than 11 lbs. and measure no more than 4 inches on a side. After being ejected from a canister housed by its mother ship, the tiny spacecraft would unfurl its miniaturized solar panels or operate on internal battery power to begin its journey to another planetary body.

Once it reached its destination, the sensor-loaded entry vehicle would separate from its service module and begin its descent through the target's atmosphere. It would communicate atmospheric pressure, temperature, and composition data to the mother ship, which then would transmit the information back to Earth.

The beauty of CubeSats is their versatility. Because they are relatively inexpensive to build and deploy, scientists could conceivably launch multiple spacecraft for multi-point sampling — a capability currently not available with single planetary probes that are the NASA norm today. Esper would equip the MIRCA craft with accelerometers, gyros, thermal and pressure sensors, and radi-

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Innovator PROFILE

10 years cutting edge 2004-2014 Chronicling Goddard Innovation

In celebration of its 10th anniversary, CuttingEdge is profiling some of Goddard's most innovative researchers. Here, we feature astrophysicist Stephen Rinehart, the principal investigator of BETTII, NASA's first spatial interferometer. Since the project began, Rinehart has hired more than 30 student interns to help build the instrument, earning him and the BETTI team the "Mentor of the Year Award" in 2014.

Stephen Rinehart and His Dream of BETTII

Astrophysicist Stephen Rinehart came to Goddard in 2001 with the dream of being part of a team that would build and launch NASA's first spaceborne far-infrared interferometer, a telescope so spatially powerful that it could discern the fine details in newly forming stars and galaxies at the edge of the visible universe.

And then, as they say, he woke up.

"We took a look at the budgetary landscape and realized that we didn't know when we could fly these missions," Rinehart said, referring to the full-blown space-interferometry missions he and his colleagues had studied over the years. Not to be deterred, the team decided, "'what the heck,' let's write a proposal to see if we can fly an interferometer on a balloon," Rinehart recalled.

NASA's First Spatial Interferometer

Next year, he and his team are slated to fly the Balloon Experimental Twin Telescope for Infrared Interferometry (BETTII), which will demonstrate spatial interferometry, an observing technique where light gathered by two, smaller telescopes is combined to effectively provide the viewing power of a much larger telescope.

The instrument is now being assembled in a high-bay laboratory. The team also includes universities in the U.S. and United Kingdom. The group plans to launch BETTII at least three times beginning in 2016.

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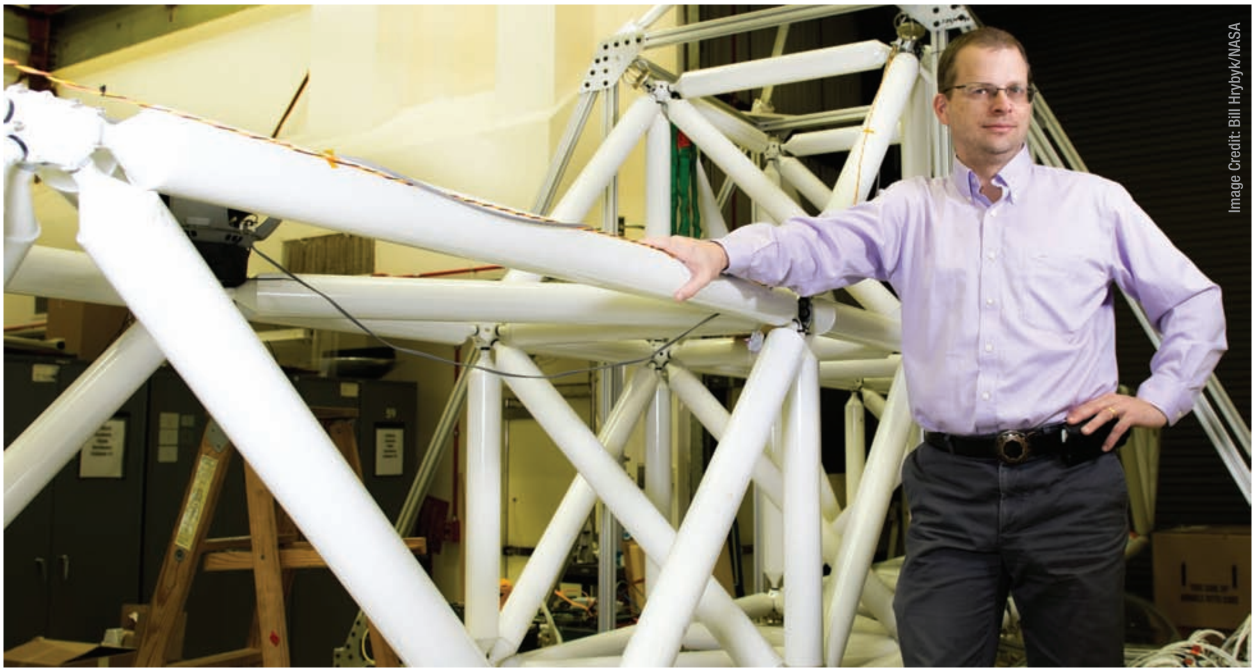

Goddard scientist Stephen Rinehart is developing NASA's first spatial interferometer, an instrument expected to fly as a balloon-borne payload. He is pictured here with the instrument's truss structure.

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Though suborbital, the instrument is a first for NASA. "This will be the first spatial interferometer NASA has ever flown," Rinehart said. "I'm psyched to use BETTII."

From its perch aboard a balloon gondola flying high into the stratosphere above Earth's obscuring atmosphere, BETTII will observe in the far-infrared band of the spectrum, taking data every 10 milliseconds of clustered stars to learn more about co-evolution, the science of how stars evolve in close proximity to one another.

It also will observe active galactic nuclei, compact, unusually bright central regions of some galaxies thought to be powered by supermassive black holes. Astronomers don't understand how they form or how they affect star formation in young galaxies.

Spectroscopic Measurements

BETTII will not produce images, as with the Hubble Space Telescope, but rather spectroscopic measurements that help scientists analyze light to reveal more about an object's physical characteristics. Due to its high-spatial resolution, scientists are expected to glean never-before-revealed details about these celestial targets and complement the high-spatial resolution of other facilities. "We expect to fill a critical need for fine-spatial details in the far-infrared wavelength bands," Rinehart said.

This expected level of performance is due to the observing technique.

In a traditional observatory equipped with a single mirror or aperture, the telescope's spatial resolution is limited by the diameter of its primary mirror. For spatial interferometers, however, the distance between the telescope mirrors determines the resolution. In BETTII's case, two small mirrors, each measuring no more than two-feet wide, will be placed on opposite ends of a 26-foot horizontal boom or truss. The infrared light that each collects will be directed through the instrument's optics and then combined to provide a sharper, more detailed view of the sky.

To get the same resolving power with a single telescope, the aperture on that telescope would have to be significantly larger, making it impractical, if not cost-prohibitive, to launch, Rinehart said.

"Interferometry is the future and BETTII is a pathfinder," Rinehart said. "I really think this instrument is the first step to what every observatory will be in the future." ❖

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Crusader, *continued from page 4*

ometers, which measure specific gases; however, scientists could tailor the instrument package depending on the targets, Esper said.

Balloon Flight to Test Stability

The first step in realizing the concept is demonstrating a prototype of the MIRCA design during a balloon mission this summer. According to the plan, the capsule, manufactured at the Wallops Flight Facility, would be dropped from the balloon gondola at an altitude of about 18.6 miles to test the design's aerodynamic stability and operational concept. During its free fall, MIRCA is expected to reach speeds of up to Mach 1, roughly the speed of sound.

"If I can demonstrate the entry vehicle, I then could attract potential partners to provide the rest of the vehicle," Esper said, referring to the service module, including propulsion and attitude-control subsystems. He added that the concept might be particularly attractive to universities and researchers with limited resources.

In addition to the balloon flight, Esper said he would like to drop the entry vehicle from the International Space Station perhaps as early as 2016 — a test that would expose the capsule to spaceflight and reentry heating conditions and further advance its technology-readiness level.

"The balloon drop of MIRCA will in itself mark the first time a CubeSat planetary entry capsule is flight tested, not only at Goddard, but anywhere else in the world," Esper said. "That, in turn, enables new opportunities in planetary exploration not available to date and represents a game-changing opportunity for Goddard." ❖

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New Earth Venture Mission to Provide Snapshot of 'Average' Atmosphere – Missing Data Point

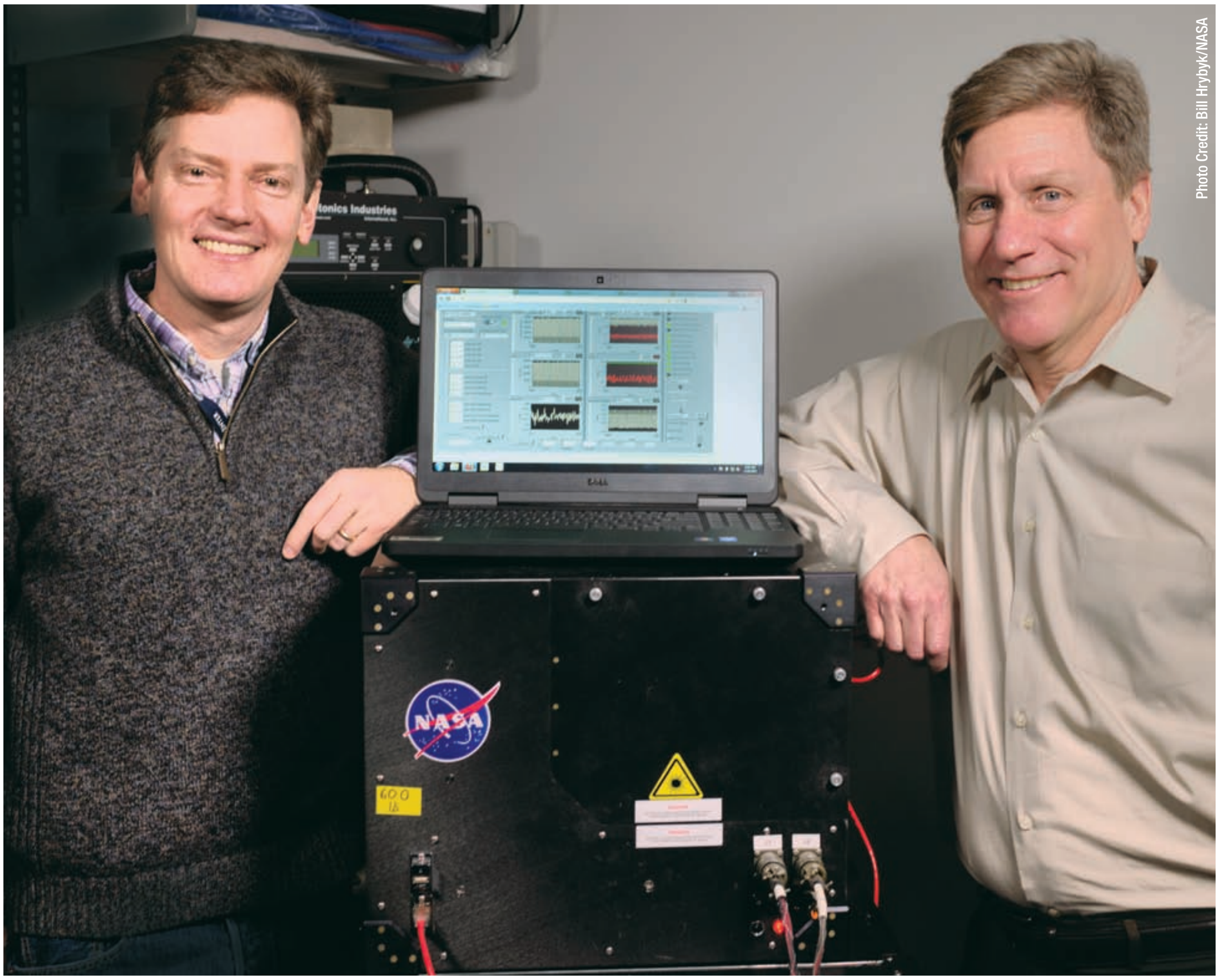

Photo Credit: Bill Hrybyk/NASA

Goddard scientists Tom Hanisco (left) and Paul Newman (right) are serving as science team co-investigators on NASA's newest Earth Venture mission, the Atmospheric Tomography Mission (ATom). One of ATom's instruments is a device (pictured here) that Hanisco developed to more efficiently measure formaldehyde.

Scientists know more about the chemical makeup of the atmosphere following forest fires, sand storms, volcanic eruptions, and other natural events than they do about its composition on less calamitous days — a missing, but important data point in climate-change research that a new NASA Earth Venture mission aims to furnish.

"What we're trying to do is get a snapshot of what the average atmosphere looks like," said Goddard scientist Tom Hanisco, who is serving as a co-investigator on the mission's science team and will be one of several principal investigators fielding an instrument on the airborne campaign expected to begin the summer of 2016. "We don't know the day-to-day. We don't know what the atmosphere looks like when there isn't a lot of pollution. What we need is pretty basic."

Just to model the basics, however, scientists will need data — and lots of it, particularly over the oceans where 70 percent of the atmosphere lies.

Led by Harvard University Principal Investigator Steve Wofsy, the Atmospheric Tomography Mission (ATom) will systematically measure reactive gases and aerosols over the Atlantic and Pacific Oceans, where the atmosphere is relatively clean and sensitive to change. By studying these regions, scientists believe they can dramatically improve their understanding of how pollutants interact and affect

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chemical processes that produce and destroy tropospheric ozone, methane, and aerosols from the atmosphere — all drivers in climate change.

The ATom team will use the data to improve climate-change computer models, develop algorithms, and validate satellite measurements, Hanisco said.

Unique Science Objectives

"The science objectives are unique," said Hanisco, who helped select the science payloads with ATom Science Team Co-Investigator Paul Newman, another Goddard Earth scientist. "This has never been done before."

The five-year Earth Venture mission, which also involves the National Oceanic and Atmospheric Administration, NASA's Ames and Langley Research Centers, the National Center for Atmospheric Research, and a number of universities across the U.S., will consist of 30-day deployments of the NASA DC-8 research aircraft equipped with 15 instruments sensitive to more than 20 different chemicals that play a role in the production and destruction of ozone, methane, and aerosols. The team plans to sample the atmosphere during all four seasons.

Each deployment, which includes 10 flights, will acquire cross-section or tomographic data of the Pacific and Atlantic, along a repeated, prescribed flight track. Flights originate at NASA's Armstrong Flight Research Center in California, proceed to the Western Arctic and North Pole, and transect the Pacific going southwards, across the South Pacific. They then head northwards through the Atlantic and return to California via Canada's high Arctic.

Most instruments sample the atmosphere every second. At latitudes above 50 degrees, ATom samples through the upper troposphere into the lower stratosphere.

"We'll likely have additional instruments," Hanisco added. "We have plenty of room and a lot of people want to fly on ATom."

Carbon Nanotube Technology Applied

He counts himself among those itching to fly. His instrument, the In-Situ Formaldehyde Instrument (ISAF), flew for the first time three years ago on the DC-8, a former passenger airplane that can fly up to 43,000 feet (*CuttingEdge*, Summer 2012, Page 9). Developed in part with Goddard research-and-development funds, the instrument is automated, lightweight, and has proven effective at measuring formaldehyde, an important tracer of volatile organic compounds (VOCs).

In general, VOCs "fuel" the oxidation processes that create smog or ozone and aerosol pollution in the atmosphere. For example, haze in the southeastern U.S. largely is the result of a VOC — isoprene — emitted by trees. When mixed with anthropogenic pollution, however, isoprene oxidizes and produces harmful ozone and organic aerosols. Because the oxidation process also produces formaldehyde, the chemical becomes a useful surrogate or tracer for a whole host of VOCs, including isoprene, terpene, and acetone, to name a few.

Hanisco's instrument gathers data on this difficult-to-measure chemical using a technique called laser-induced fluorescence (LIF). With LIF, ambient air is drawn into a tube and then illuminated with a laser. The chemical then fluoresces, which is measured with a photon-counting photomultiplier tube. The instrument has proven to be 10 times smaller, 10 times more sensitive, and 10 times faster than the previous state-of-the-art instrument.

Since the instrument's debut, Hanisco has further improved the instrument by applying a carbon-nanotube (CNT) coating to the instrument's baffle, which absorbs scattered laser light that can contaminate measurements. The coating, advanced by Goddard technologist John Hagopian, consists of a thin, highly uniform layer of multi-walled nanotubes made of pure carbon. Among other applications, it is highly effective at absorbing stray light due to the fact that the carbon atoms occupying the tiny nested tubes absorb the light and prevent it from reflecting off surfaces.

"The CNT-coated baffles are about five to 10 times better at absorbing the scattered light than the best black paint," Hanisco said. Until now, applying black paint on instrument components was the preferred technique for absorbing stray light.

In addition to formaldehyde, ATom will collect measurements of carbon dioxide, methane, nitric acid, peroxides, aerosols, and ozone, among others. "Just to model the basics, you need to know everything," Hanisco said. "You have to get every input and you have to do it well." ❖

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Potentially Revolutionary Mission On Track for 2016 Launch

A potentially revolutionary Goddard-led mission that embodies the virtues of faster, less expensive access to space has sailed past all major development milestones and is scheduled to be delivered to Cape Canaveral on time for its October 2016 launch.

"We've stayed on schedule, and in fact, have five to six months of slack," said Keith Gendreau, the principal investigator of the Neutron-star Interior Composition Explorer/Station Explorer for X-ray Timing and Navigation Technology (NICER/SEXTANT). "We should be ready this time next year" to deliver the instrument for integration aboard the SpaceX Dragon transfer vehicle on a Falcon 9 rocket.

One-of-a-Kind Multi-Purpose Investigation

NICER/SEXTANT, which NASA selected in 2013 as its next Explorer Mission of Opportunity (*CuttingEdge*, Spring 2013, Page 2), is a one-of-a-kind investigation that not only will gather important scientific data, but also demonstrate groundbreaking technologies — all from a relatively low-cost instrument that takes advantage of an already-existing platform, the International Space Station (ISS).

Once the instrument deploys next year as an external attached payload on one of the ISS ExPRESS Logistics Carriers, its 56 X-ray optics and silicon detectors will observe and gather data about the interior composition of neutron stars and their pulsating cohort, pulsars.

Although these objects emit radiation across the spectrum, observing in the X-ray band offers the greatest insights into these unusual, incredibly dense celestial objects that if compressed any further would collapse completely into black holes. The mission will shed light into their structure and allow astronomers to observe the stars' tremendously strong magnetic fields and other physical properties.

In pulsars, the magnetic poles are especially luminous, affording an opportunity to also demonstrate celestial-based or X-ray navigation (XNAV), a capability that could revolutionize NASA's ability to pilot to the far reaches of the solar system and beyond.

Technicians assemble a new 25-foot test facility, equipped with a 3.3-foot parabolic optical mirror, which will be used to align NICER/SEXTANT's 56 optics and detectors.

Due to their rapid pulsations, with repetition periods that range from seconds to milliseconds, the powerful beams of radiation emanating from their magnetic poles sweep around much like a lighthouse, and are seen as flashes of light on Earth. Because of their predictable pulsations, pulsars can provide high-precision timing just like atomic-clock signals supplied through the Global Positioning System (GPS), which weaken the farther one travels out beyond Earth and the GPS constellation.

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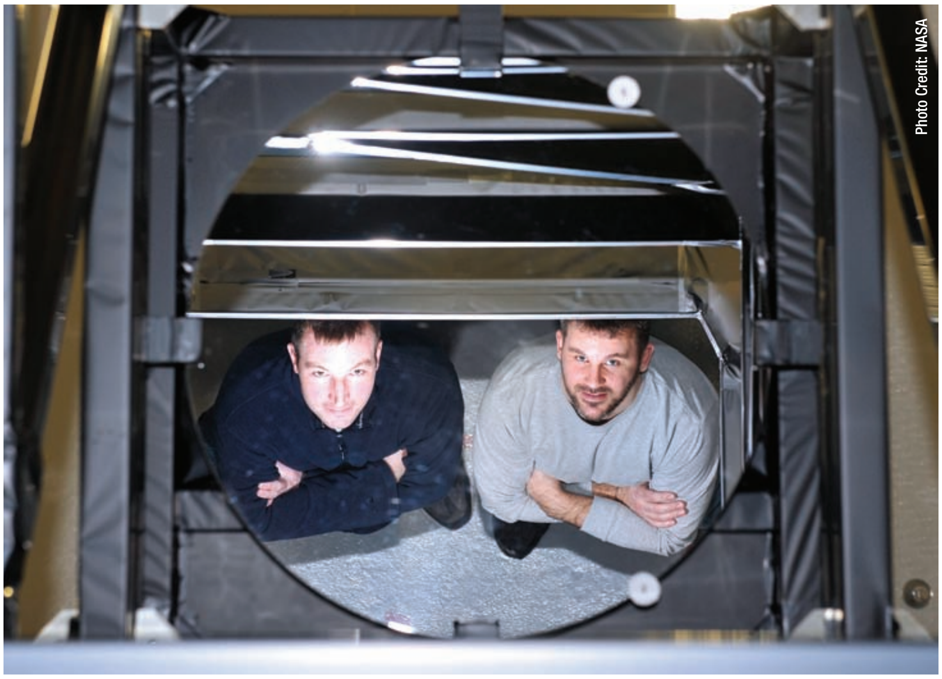
Two Birds with One Stone

To demonstrate XNAV, the payload will detect X-ray photons within the pulsars' sweeping beams of light to estimate the arrival times of the pulses. With these measurements, the system will use specially developed algorithms to stitch together an onboard navigational solution.



Technicians Alex Schaeffer (left) and Eric Norris (right) are seen reflected in a 3.3-foot-diameter parabolic mirror suspended 24 feet above the ground in one of Goddard's high-bay facilities. Mounted at the top of a custom "collimator tower," the mirror provides a parallel beam of light that will allow the team to co-align NICER/SEXTANT's 56 X-ray optics and star tracker. A clean tent recently erected around the tower has transformed the high bay into the mission's integration and test facility.

The NICER/SEXTANT team, which also includes the Massachusetts Institute of Technology (MIT), Moog Inc., the Naval Research Laboratory, and universities across the U.S., Canada, and Mexico, also may demonstrate a second technology — X-ray communication — that, if advanced, potentially could allow space travelers in the future to transmit gigabytes of data per second over interplanetary distances.

At the heart of this potential demonstration is the Modulated X-ray Source (MXS), which the team developed to test and validate the XNAV concept. The technology generates rapid-fire X-ray pulses, turning on and off many times per second, encoding digital bits for transmitting data. If the team attracts additional support, perhaps from other government agencies interested in advancing X-ray communication, the team plans to develop an MXS-based transmitter that would fly on a future ISS supply spacecraft. As the craft approached the space station, MXS would transmit data via the modulated X-rays, which the NICER/SEXTANT hardware would then receive.

Model of Efficiency

Although its mission is ambitious, the NICER/SEXTANT instrument itself is a model of efficiency, both in terms of what it will do but also how it was assembled, Gendreau said. "We made a conscious decision to use COTS (commercial-off-the-shelf) parts where we could, taking carefully considered risks where it's warranted. I think NICER/SEXTANT is a nice balance. It's all about risk management."

The calculated strategy appears to have paid off. Last year, the mission passed the first of several important milestones, including the Critical Design Review and various ISS safety reviews. Upon learning that the station would not be providing the voltage needed to run the instrument, the team designed and is now building a space-qualified power converter that converts the ISS-supplied 120 volts to 28 volts — in time to be included in the mission's integration schedule. "We've turned that into a success story," Gendreau said. "Again, it's because we have a small, nimble team."

The team now is busy testing the instrument's 56 X-ray optics, built in-house and based on a design created by Goddard scientist Peter Serlemitsos, who has created the replicated foil mirrors for other X-ray missions. The team built a 25-foot "collimator" tower, equipped with a 3.3-foot-diameter parabolic optical mirror, which will be used to co-align the instrument's 56 optics and star tracker.

"It's really coming together," Gendreau said. "Our goal is to get this done under budget." ❖

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3D Printing Reveals Never-Before-Detected Details of Superstar Eta Carinae

In what is believed to be a first, a team of Goddard scientists has used 3D printing to create a model of the mysterious Eta Carinae star system, discovering never-before-revealed details about the most luminous and massive stellar system within 10,000 light-years of Earth.

Image Credit: Bill Hrybyk/NASA

In what is believed to be a first, Thomas Madura has used 3D printing to create models (pictured here) of the mysterious Eta Carinae star system, discovering never-before-revealed details about the most luminous and massive stellar system within 10,000 light-years of Earth.

Although Goddard technologists are experimenting with 3D or additive manufacturing to build complicated instrument components, post-doctoral fellow and theorist Thomas Madura said he and his team are believed to be the first to use the technology to produce a 3D-printed model from a supercomputer simulation based on 11 years of observations by NASA satellites and ground-based telescopes. The end result is the most comprehensive picture of Eta Carinae to date, Madura said.

"It wasn't until I created the 3D-printed model that we could see what we would have never known," Madura said, adding that the computer simulation kept the details hidden. "As far as I know, no one has done [3D printing of a computer simulation] before. It shows how this technology can be used to better understand complex physical interactions" between two enormous objects that have intrigued scientists for decades, he said.

Located about 7,500 light-years away in the southern constellation of Carina, Eta Carinae comprises two massive stars whose eccentric orbits bring them unusually close together every 5.5 years. In the 1840s, the system became the second brightest object in the sky when it exploded twice for reasons astronomers still don't understand, ejecting enormous quantities of material that created a bipolar nebula that now spans 1 light-year in diameter. Amazingly, these events did not destroy the star system.

Both stars produce powerful gaseous outflows called stellar winds that enshroud the stars. Although the phenomenon has stymied efforts to directly measure their properties, astronomers have established that the brighter, cooler primary star has about 90 times the mass of the sun and outshines it by 5 million times. Its smaller, hotter companion has about 30 solar masses and emits a million times the sun's light.

They also have observed that at closest approach, or periastron, the stars are 140 million miles apart, or about the average distance between Mars and the sun. Astronomers observe dramatic changes in the system during the months before and after periastron. These include X-ray flares, followed by a sudden decline and eventual recovery of X-ray emission; the disappearance and re-emergence of

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structures near the stars detected at specific wavelengths of visible light; and even a play of light and shadow as the smaller star swings around the primary.

According to the team's computer simulation, the interaction of the two stellar winds accounts for many of the periodic changes observed in the system. The primary star's wind blows at nearly 1 million mph and is especially dense, carrying away the equivalent mass of our sun every thousand years. By contrast, the companion's wind carries off about 100 times less material than the primary's, but it races outward as much as six times faster.

Madura's simulations, which were performed on the Pleiades supercomputer at NASA's Ames Research Center, reveal the complexity of the wind interac¬tion. When the companion star rapidly swings around the primary, its faster wind carves out a spiral cavity in the dense outflow of the larger star.

To better visualize this interaction, Madura decided to convert the computer simulations to 3D digital models, which he fed into a consumer-grade 3D printer. To his surprise, the resulting solid 3D-printed model revealed lengthy spine-like protrusions or "fingers" in the gas flow along the edges of the cavity — features that hadn't been noticed before in the computer simulations.

"We think these structures are real and that they form as a result of instabilities in the flow in the months around closest approach," Madura said. "I wanted to make 3D prints of the simulations to better visualize them, which turned out to be far more successful than I ever imagined," he said, adding that the results will be published in the journal, Monthly Notices of the Royal Astronomical Society.

Madura said the exercise has other important implications. "The success of our work helps highlight the important role that 3D printing can play in the visualization and understanding of complex 3D time-dependent simulations. It has the potential to provide an entirely new method for researchers to visualize, understand, interpret, and communicate their science results," he said. ❖

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Goddard Scientist Embraces New Crowdsourcing Technology to Search for Planetary Disks

If Goddard scientist Marc Kuchner had the ability to clone himself, he may not have needed to enlist the help of hundreds of citizen "detectives" now helping him find thousands of new planetary systems around other stars.

In what he believes is a first for Goddard, Kuchner has recruited thousands of volunteers worldwide who are using DiskDetective.org — a NASA-sponsored citizen science website — to classify objects imaged by NASA's Wide-field Infrared Survey Explorer (WISE).

He's happy cloning wasn't an option. The volunteers have far surpassed anything a team of professional scientists could have managed in the same period, he said.

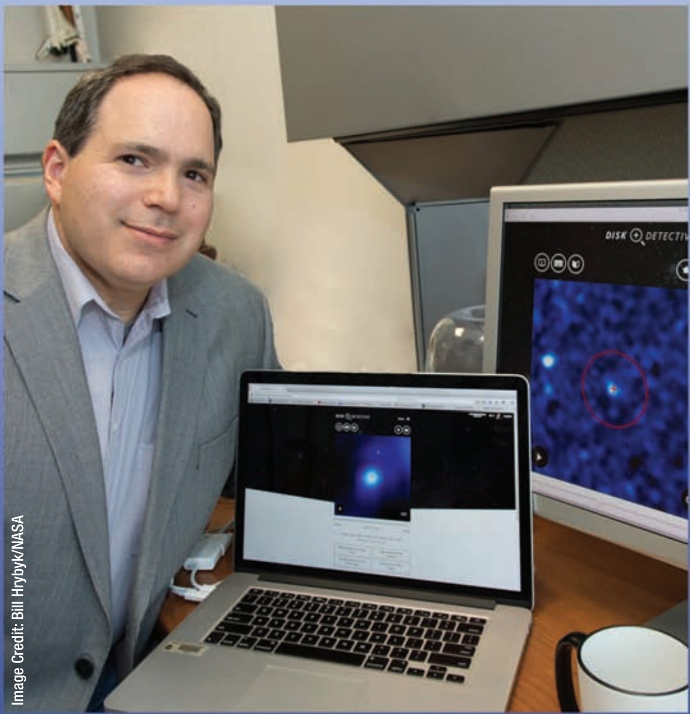
The project's goals are to find two types of developing planetary environments in the WISE data. The first, known as a young stellar object (YSO) disk, typically is less than 5 million years old, contains large quantities of gas, and often is found in young star clusters. The second planetary habitat, known as a debris disk, tends to be older than 5 million years, holds little or no gas, and possesses belts of rocky or icy debris that resemble the asteroid and Kuiper belts found in our own solar system.

The classifications will give scientists a better understanding of the origin of the solar system and provide a crucial set of targets for future planet-hunting missions, Kuchner said.

Computer searches already have identified some objects observed during the WISE survey as potential dust-rich disks. But software can't always distinguish them from other infrared-bright sources, such as galaxies, interstellar dust clouds, and asteroids. There may be thousands of potential planetary systems still lurking in the WISE data, and the only way to know for sure is to inspect each source by eye.

"I couldn't do this by myself," Kuchner said, explaining his reasons for embracing open innovation through social media and other online venues to

Continued on page 13



Marc Kuchner is using crowdsourcing to discover new planetary systems around other stars. Since he began the project, thousands of people worldwide have visited DiskDetective.org to make classifications.

The marked asymmetry of the debris disk around the star HD 181327 (shown here in a Hubble image) suggests it may have formed as a result of the collision of two small bodies. DiskDetective aims to discover many other stellar disks using volunteer classifications of data from NASA's WISE mission.

help conduct science. "WISE identified 747 million sources, which are just too many for me to look at."

Kuchner recognized that searching the WISE database for dusty disks was a perfect opportunity for crowdsourcing. He worked with NASA to team up with Zooniverse, a collaboration of scientists, software developers, and educators who collectively develop and manage citizen science projects, such as DiskDetective, on the Internet.

At DiskDetective.org, volunteers watch a 10-second "flip book" of a disk candidate shown at several different wavelengths as observed from three different telescopes, including WISE. They then click one or more buttons that best describe the object's appearance. Each classification helps astronomers decide whether background galaxies, interstellar matter, or image artifacts have contaminated the images or whether the images reveal interesting disk candidates in need of further study.

"I think this is the first time a Goddard principal investigator has done a crowdsourcing project on this scale," Kuchner said.

Since the project began, Kuchner said more than 28,000 visitors from around the world have participated in the project, logging nearly 1.2 million classifications. Those classifications have yielded more than 658 objects of interest, Kuchner said. Scientists now are conducting follow-up investigations of those objects with ground-based telescopes in Arizona, California, New Mexico, Argentina, and Chile. The team expects to wrap up the current project sometime in 2018, with a total of about 3 million classifications and perhaps 1,000 disk candidates. The researchers then plan to add an additional 140,000 targets to the site for analysis.

What's especially impressive, said Kuchner, is how much the volunteers have done, going above and beyond what he had anticipated. They have translated the site into eight foreign languages, including Romanian, Mandarin, and Bahasa. They have produced their own video tutorials on using DiskDetective. And they have become crucial extensions of the science team, getting together on Google hangouts and creating Google spreadsheets to help research targets for upcoming observing runs.

"I think people are hungry to find a way to have a more meaningful NASA experience," Kuchner said. "For me, this project gives people an opportunity to discover. We're discovering together." ❖

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Fearsome Foursome, *continued from page 3*

Enter a New-Fangled Antenna

Communicating commands to the MMS fleet also required the MMS team to rethink the onboard hardware it would use, said Adán Rodríguez-Arroyo, who developed a new-fangled, diminutive S-band antenna that met the mission's communications requirements. "It is a good example of innovation at Goddard," he said.

Typically, omnidirectional antennas on spinning spacecraft are positioned in the middle of a spacecraft to assure a direct line of sight to ground stations. With MMS, however, instrument booms needed to occupy that real estate, leaving mission planners with very few options as to where to place hardware so essential for receiving and transmitting telemetry, housekeeping, and scientific data. Further complicating the challenge was the fact that the antennas could not be too close to the surface of the spacecraft because of potential degradation caused by reflection and refraction.

This Goddard-developed S-band communications antenna is one of many enabling technologies on NASA's MMS mission.

The new S-band antenna overcame these obstacles. It incorporated two 3-inch antenna elements integrated atop a two-foot mast, all into one assembly that neither interfered with other instruments nor added too much weight or complexity. Each spacecraft carries two, one on top of the observatory, the other below.

"We needed to keep the antenna light because every pound matters. Furthermore we didn't want the antenna to block an instrument's view," Davis said. "It's a spindly little thing. I can't believe it can communicate from half-way to the Moon."

So Much Data, So Little Bandwidth

However, it wouldn't have mattered how well the antenna performed had it not been for a data-compression technology developed by now-retired Goddard technologist Penshu Yeh. The communications hardware would have been overwhelmed by the copious amounts of data collected by one instrument in particular, the Goddard-developed Fast Plasma Investigation (FPI).

Designed to measure the pressure, temperature, and heat flow of plasmas, FPI is expected to generate a megabyte of data per second on each of the four spacecraft — a rate analogous to streaming video over a computer. While easy on Earth with high-speed Internet, it's difficult in space where the data rate would quickly swamp the mission's S-band allocation for downlinking data.

"We were up against basic laws of physics," said Tom Moore, Goddard's MMS project scientist who also worked on FPI. "There's only so much data you can get down."

In 2004, Yeh had already begun developing a next-generation data-compression algorithm on application-specific integrated circuits. Four years later, she and her partner, the University of Idaho's Center for Advanced Microelectronics and Biomolecular Research, successfully fabricated two radiation-hardened processors — the Discrete Wavelet Transformer and a Bit Plane Encoder, funded by NASA's Space Communication and Navigation office. The chip set can compress 20 megabytes of data per second, far surpassing the instrument's data-compression needs.

The technology also enables two types of data products. Fast survey provides a comprehensive view of the distribution of ions and electrons in space, including their direction and energy, as the spacecraft speed through the reconnection zones. Burst data, on the other hand, delves deeper into the measurements, providing details at millisecond time intervals. Scientists will inspect the fast survey data daily to determine which time intervals to downlink in the burst set, said FPI Principal Investigator Craig Pollock.

"With this data, we'll be seeing more than we could before," Moore said, adding that the reconnection zones — where magnetic fields nearly touch — are narrow. "Previously, we got the big picture, but didn't have the time resolution to see the details. This mission was a long time coming. We're anxious to reap the rewards." ❖

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The CAVE, *continued from page 3*

visualizations, users actually can walk around the object they've created.

Because of this facility, one of the four spacecraft already existed long before the MMS team bent its first sheet of metal. It existed as a 3D hologram, suspended in a pitch-black, room-size facility, surrounded by millions of stars.

Green Cleanroom

Once the team settled on the spacecraft design, it needed to find a space large enough to simultaneously build and integrate four spacecraft. Goddard's world-renowned High Bay Clean Room was booked, which forced the MMS team to look elsewhere. "The MMS project realized that it had to build its own cleanroom," said MMS Deputy Project Manager Brent Robertson.

The team converted a 4,200-square-foot former warehouse into a state-of-the-art "smart cleanroom," equipping the facility with 153 high-efficiency particulate air fans that removed contaminants that could damage highly sensitive instruments.

The filtering system did its job: the air inside the sprawling facility contained no more than 10,000 particles per cubic feet, and those that remained, measured about half the width of a human hair. It accomplished this while consuming 30 percent less energy under low-load conditions — a savings due in large part to a computer-controlled sensing system that switched off lights when no one was using the facility and ordered the fans to slow down when monitors sensed that the room had reached the required cleanliness levels.

Color-Coding

Even before moving into the new cleanroom, mission planners understood they needed to adopt a new set of procedures and processes just to stay organized, particularly when carrying out system testing on each. "It's so important that a mistake not be made and it's easy to get confused," Davis said.

The solution? They color-coded.

Each satellite was assigned a specific color — yellow, blue, green, and purple. Not only did the color identify the individual satellite, it also correlated with its paperwork. Even the ground system has adopted the color-coding to differentiate one satellite from another. ❖

Photo Credit: Chris Gunn/NASA

Hundreds of Goddard employees and contractors used a new state-of-the-art, "green" cleanroom to build and integrate the four MMS spacecraft.

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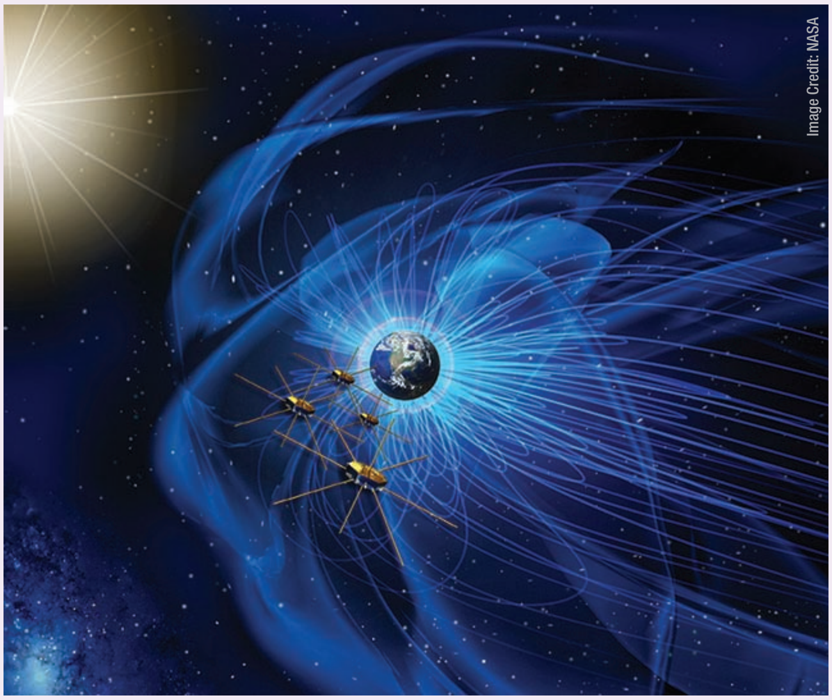
Moving the Laboratory Into Space

Although scientists have observed the effects of magnetic reconnection in space, they never have directly measured the process. NASA's Magnetospheric Multiscale (MMS) mission will change that by using the Earth's magnetosphere as a laboratory to study the phenomenon in action.



This artist's concept of NASA's MMS mission, which consists of four identical observatories, will fly in a tight formation and provide the first 3D view of magnetic reconnection.

Beginning this September, the four-spacecraft mission will begin studying this universal occurrence that occurs wherever charged gases, called plasma, are present. While rare on Earth, plasma makes up 99 percent of the visible universe, fueling stars and filling the near vacuum of space. Plasmas behave unlike anything experienced on Earth because they travel with their own set of magnetic fields trapped inside the material.

Under normal conditions, these fields don't break or merge, but sometimes when they get close to each other in thin layers just miles thick, the fields change and realign into new configurations. The effects can be explosive. The reconnection taps into the stored energy of the magnetic field, converting it into heat and kinetic energy that send particles streaming out along the field lines at nearly the speed of light.

Although this phenomenon occurs across the universe, it is of particular interest to scientists here on Earth because it can initiate gigantic eruptions from the sun many times the size of Earth. These eruptions can cause intense storms in the form of solar flares, coronal mass ejections (CMEs), and the transfer of energy from the CME to Earth's protective magnetosphere. This transfer triggers brilliant aurora typically over the poles, but it also can disrupt satellite communications and cause power blackouts.

Scientists also are interested in understanding magnetic reconnection because of its disruptive role in laboratory-based fusion plasmas. The understanding gained through MMS has the potential to enable better control of the fusion-plasma environment, yielding a potential renewable energy source for humanity, said Goddard scientist Craig Pollock, principal investigator of MMS's Fast Plasma Investigation.

During the MMS mission, the spacecraft will pass through known areas of reconnection in Earth's magnetosphere to study the phenomenon up close. With this information, scientists will get their first chance to watch reconnection from the inside as it's occurring. By studying it in Earth's magnetosphere, scientists will open windows to understanding what happens on smaller scales in laboratory plasmas and on larger scales across the universe. ❖

Cutting edge Goddard's Emerging Technologies

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