BRACING FOR

AS OUR DAILY LIVES DEPEND MORE ON SATELLITE COMMUNICATIONS, LOOMING SPACE STORMS THREATEN TO WREAK HAVOC. BU RESEARCHERS ARE BUILDING THE FIRST LINE OF DEFENSE.

BY CHRIS BERDIK

After a coronal mass ejection explodes from the surface of the sun, its plasma cloud hits the Earth's magnetic field, spawning storms that can disrupt communications, damage satellites, and cause power blackouts.

THE STORMS

PHOTO COURTESY OF SOHO (ESA & NASA)

ON OCTOBER 18, 2003, scientists at the Space Environment Center in Boulder, Colorado, saw something alarming. The consoles in the center's forecast room were lighting up with data feeds from satellites and ground-based observatories tracking the sun's X-ray and radio emissions, as well as the solar wind — high-energy protons and electrons streaming toward Earth at millions of miles an hour. With little warning, a massive and growing cluster of sunspots had appeared on the solar surface. Over the next few days, the scientists spotted two more sunspot groups, one of them thirteen times the size of Earth. To the forecasters, that meant one thing: a monster storm was brewing on the sun.

The center, since renamed the Space Weather Prediction Center (SWPC), immediately issued warnings of imminent solar eruptions that could spew high-energy particles into space, irradiating astronauts, knocking out satellites, and overloading electric power grids on Earth. Indeed, before the storms subsided three weeks later, they had destroyed at least one satellite and damaged others, triggered power blackouts, disrupted airlines, and postponed a lot of business dependent on global positioning systems (GPS). The northern lights, colorful evidence of space weather activity, were spotted as far south as Florida. In addition, seventeen major solar flares, the largest of which could have exposed astronauts to the equivalent of 100 instantaneous chest X-rays, erupted during the storms,

CAS ASTRONOMY PROFESSOR HARLAN SPENCE DESIGNED A PROBE TO MEASURE THE EFFECTS OF COSMIC RAYS ON HUMAN TISSUE.

says, observational work using SOHO keeps him focused on the big picture of what he's modeling. "It goes back to being a kid," he says. "I realized that being unfit and having bad eyesight meant I couldn't be an astronaut, and so this was the next best thing."

STORM CHASERS

In January 2004, President George W. Bush announced a new agenda for NASA: the agency would pursue "new journeys to worlds beyond our own." Bush proposed that humans return to the lunar surface as early as 2015, create a permanent outpost there for research and mineral exploration, and plan for a manned mission to Mars.

To accomplish this without putting astronauts at serious risk, NASA must predict solar storms days in advance. That's particularly important for a Mars mission, during which astronauts would spend a lot of time beyond the protection of the Earth's magnetosphere.

According to Schwadron, the astronauts of the Apollo missions in the late 1960s and early 1970s were lucky to have escaped serious injury from space storms. "If we had had more missions, eventually there would have been a flare or some very large radiation event from the sun that would have wreaked havoc," he says. "The goal is to be able to give days and days of warning, so astronauts will be able to explore those environments."

CISM's work is not the only BU-led effort to help achieve that goal. Schwadron, for instance, is partnering with radiation biologists on a project known as the Earth-Moon-Mars Radiation Exposure Module (EMMREM), a three-year NASA-funded initiative that began in 2006.

"We have a couple of different models that we're putting together," he says. "One is a model of how charged particles are generated and move through space. The other is a model that predicts how that radiation will interact with atmospheres, with shielding on spacecraft, and with human tissue."

Schwadron's team will use data generated by CISM's solar wind models. They will also refine their own model with measurements from a probe designed by Harlan Spence (CAS'83), a CAS professor of astronomy, and scheduled for launch later this year on board NASA's Lunar Reconnaissance Orbiter. The instrument, the Cosmic Ray Telescope for the Effects of Radiation, or CRaTER, is made of tissue-equivalent plastic and will measure the effects of cosmic ray radiation on the human body, which could include radiation sickness and cancer.

Of course, the true test for both EMMREM and the CISM models is their usefulness in real-time forecasting at places such as the Johnson Space Center, where members of the Space Radiation Analysis Group wear pagers that alert them to major changes in the twenty-four-hour data feed from solar observatories and satellites.

"If the pager messages tell us we've gone above certain thresholds, then we come in and stay around the clock until things have calmed back down," explains Steven Johnson, a senior member of the Space Radiation Analysis Group.

"You start to work with these guys, and immediately you realize what they're facing," Schwadron says. "When we give them a very sophisticated model that has beautiful pictures of coronal mass ejections and can illustrate solar shock waves in 3-D, they're not terribly impressed if it doesn't give them any extra warning capability."

Consequently, CISM recently turned over two coupled models to SWPC for testing and refinement (essentially, both halves of the sun-to-Earth model CISM plans to produce).

"Making a model operational is a huge challenge," says CISM's Hughes. "It can't crash. It's got to work under a whole range of inputs. You can't tune it after the fact to make yesterday work better."

Hughes points out that while researchers in lab conditions can clean up the data used in their models, operational models need to assimilate live feeds from observatories and satellites, "and that data has glitches and gaps that the model has to deal with on the fly and in a reasonable time."

After each round of validating by CISM researchers and further testing by forecasters, the model's physics and the code are tweaked. The goal is to show that physics-based models are superior to the simpler empirical models, says Hughes, not only for understanding the science of space weather, but for the forecasters safeguarding the world's communications, infrastructure, and astronauts. It's not about achieving a perfect model, he adds. "We're not going to get there in our lifetime," he says, "or in our graduate students' lifetimes." But even an imperfect model could save billions of dollars in avoided space weather disruption of communications satellites, power grids, and airlines, according to the 2006 federal report on space weather preparedness. The BU researchers hope to have a model that will allow at least three days of warning by 2012, just about the time the sun will be entering its next peak of storming.

For now, the race is on. **B**

✱ web extra

Short videos of computer simulations created by the Center for Integrated Space Weather Modeling can be found at www.bu.edu/bostonia.

the relative scarcity of historical data on the rare events that are typically the most severe.

"If you run into a situation that you've never seen before, which happens a lot in space weather, then it's very difficult to use empirical models to make forecasts," Gross says.

"We need to understand the complexity of this huge system, with the sun and the Earth, plasmas and magnetic fields, and how it all interacts," says Quinn. "What are the rules that Mother Nature has given us?"

So CISM has been building physics-based models similar to those developed for terrestrial weather forecasting over the past fifty years. Instead of relying on data from past storms, these models create forecasts based on applicable laws of physics at work in the sun's atmosphere, within the solar wind, and near the Earth.

In their quest to mimic Mother Nature with numbers, CISM researchers didn't start from scratch. Beginning in the 1980s, scientists at several universities and research labs (many now CISM partner institutions) were developing models that focused on four different portions of the sun-to-Earth system — the sun's outer atmosphere, or corona, the solar wind, the Earth's protective magnetosphere, and the ionosphere in our upper atmosphere.

"At the core of each of these models is a grid," explains Quinn. That is, the region of space or atmosphere being modeled is plotted by a three-dimensional series of points. Computers use variables, such as pressure and temperature, at each point to solve equations that represent the operative laws of physics. Change the density of these points, says Hughes, and you vary the resolution of the model.

"Where conditions are relatively uniform, you can have these points far apart," he says. "Where things change rapidly, you need a lot of them to describe the change."

The grids for the CISM models often contain more than a million points, necessitating a degree of number crunching that Hughes says can lead to "computational complications." For example, a magnetosphere model adopted by CISM was developed on a grid that moved in a uniform direction dictated by the flow of the solar wind. Meanwhile, the grid of an independently developed ionosphere model rotates with the Earth.

"Each model developer did the sensible thing for his own purposes," says Hughes. "But now you've got a rotating grid sitting inside a fixed grid, and they need to talk to each other."

While six BU faculty members work in some capacity with CISM, much of the work of joining the models, known as coupling, is done by graduate students and postdoctoral researchers, among them Viacheslav "Slava" Merkin, a senior research associate in the BU astronomy department. Merkin has been working for more than three years to join the magnetosphere model with the ionosphere model. One of his tasks is writing code that can, as he says, "do all the dirty work of coupling," such as interpolating data from one grid to another and converting units used to measure variables that can change from model to model.

Another senior research associate in astronomy, Mathew Owens, is testing a model of the sun's corona coupled with a model of the solar wind. Owens and his team validate the forecasting capabilities of this combined model by measuring predictions it makes against actual solar observations and the resultant solar wind readings at SOHO.

Despite all the number crunching, Owens

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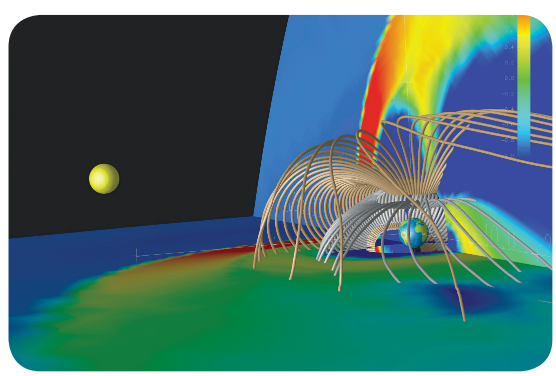
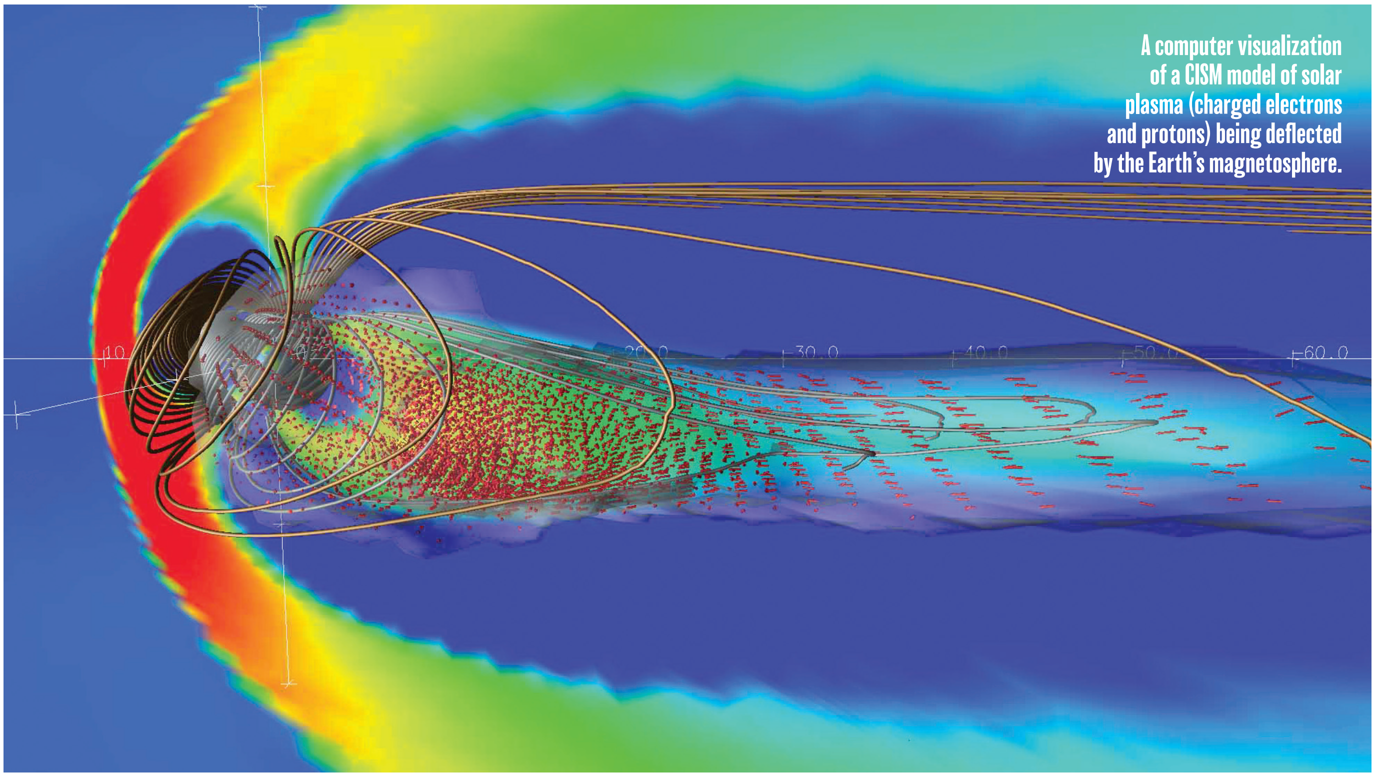
CAS Astronomy Professor Jeffrey Hughes and other CISM researchers work with space-weather models that track the electromagnetic forces generated when the solar wind interacts with the Earth's protective magnetosphere. The yellow ball is the sun.



PORTRAIT PHOTOS BY VERNON DOUCETTE; INSET IMAGE COURTESY OF CISM AND BU'S SCIENTIFIC COMPUTING AND VISUALIZATION GROUP



A computer visualization of a CISM model of solar plasma (charged electrons and protons) being deflected by the Earth's magnetosphere.

IMAGE COURTESY OF CISM AND BU'S SCIENTIFIC COMPUTING AND VISUALIZATION GROUP

Another space storm danger is solar flares, intense bursts of radiation that can reach Earth in minutes, irradiating astronauts and disrupting radio communications, which increasingly concerns commercial airlines. Since the end of the Cold War, airlines have opened new time- and money-saving routes over the North Pole for flights between North America and Asia. In 2005, more than 3,700 commercial flights used this polar route, ten times the number in 2000. But flying over the pole also renders pilots reliant on high-frequency radio communications, which are vulnerable to solar storms, and every diverted flight costs its airline about $100,000. Likewise, a satellite knocked out by a solar storm can cost hundreds of millions of dollars to replace; the Department of Defense spends $500 million a year mitigating the effects of space weather, according to 2003 congressional testimony by a former SWPC director.

"Satellites now impact everything from when you use your credit card at the gas pump to when you make a call on your cell phone," says Howard Singer (GRS'72), chief of SWPC's science and technology infusion branch. But this steady move to satellite-dependent living is on a collision course with an eleven-year solar cycle expected to peak in 2011, initiating several years of increased space weather activity. In fact, the 2003 storms occurred more than three years *after* the last high point in the solar cycle.

"I think we're coming into an era where the growth of demand for our services is going to be really, really big," Singer says. If traffic on the SWPC Web site is any indication, that demand is already here. In October 2003, daily hits to the site spiked from an average of half a million to nineteen million at the height of the storms.

But when Singer compares SWPC's forecasting abilities to sister organizations such as the National Hurricane Center and the National Storm Center, he admits that "we're a little behind."

For one thing, compared to earthly forecasts, space weather predictions can depend on relatively few observation points for real-time weather data. Two aging satellites, the Solar and Heliospheric Observatory (SOHO) and the Advanced Composition Explorer (ACE), are stationed about a million miles upstream of Earth, monitoring the solar wind as it nears our magnetosphere and providing about an hour's warning of approaching storms.

"That's great for determining what space weather conditions are right now," says Nathan Schwadron, a CAS associate professor of astronomy. "It's terrible for providing actual warning from those predictions."

What's more, SOHO and ACE are vulnerable to the same high-energy particles they're tasked to observe. Space weather forecasters also use several ground-based solar observatories, magnetometers, cosmic ray observatories, and radars, most of which were not originally designed for solar forecasting.

"We've sort of cobbled together a system of space weather observation from the things that we've had available," says Schwadron. "It's not ideal."

MIMICKING MOTHER NATURE

Warnings issued for the 2003 solar storms by SWPC and the Johnson Space Center were based largely on empirical models — probabilities of certain outcomes based on observations of the sun and solar wind calculated with data from historic solar conditions and the resulting storms.

Such empirical models are handy, because their relative simplicity means they can be run quickly on small computers. But they're limited too, explains Nicholas Gross (GRS'95), education director of CISM and the Center for Space Physics, by the sparsity of observation points between the sun and the Earth and by leading NASA to repeatedly direct the International Space Station crew to hunker down in shielded areas of the spacecraft.

The damage could have been worse if SWPC and NASA had not sent more than 250 warnings and alerts to astronauts, airlines, electric companies, and the public. Still, experts warn that when the next major space weather event blows in from the sun, we may not be so lucky.

Currently, the solar storm cycle is in a quiet period, but scientists know that things will be revving back up in the next five to ten years, just as NASA prepares to send astronauts on extended missions to the moon and on to Mars and as the world becomes increasingly reliant on space-based technologies. The looming problem, according to the 2006 federal Report of the Assessment Committee for the National Space Weather Program, is that the nation's solar storm forecasting capabilities "lack sufficient reliability" and "do not provide useful lead time or information on the magnitude and duration of the event."

"All this technology, from GPS to wireless communication, is making life better, but then you become more dependent on it and potentially vulnerable to its glitches," says Jeffrey Hughes, a College of Arts and Sciences professor of astronomy.

Hughes works on the sixth floor of CAS, overlooking the Charles River, in an office decorated with antique maps of his native North Wales and an Inuit bone carving that he acquired while studying the northern lights in the Canadian Arctic. Around the corner from his office, past an Ansel Adams print of the moon rising over Half Dome in Yosemite, sits Jack Quinn, a sharp-featured Colorado native and a research professor of astronomy. Together, Hughes and Quinn head up the multi-institute Center for Integrated Space Weather Modeling (CISM), which works on the front lines of a national effort to increase our preparedness for future solar storms. In addition, some fifty faculty and graduate students from astronomy and the College of Engineering are affiliated with BU's Center for Space Physics, and many of them also focus on space weather, researching the solar wind, planetary atmospheres, and the movement of high-energy particles in space. They also lead the development of radiation probes and electron imagers that future NASA missions will use to study the Earth's magnetosphere and the dangers awaiting astronauts who might return to the moon or venture on to Mars.

The National Science Foundation established CISM in 2002 with $40 million spread over ten years and one goal: to make solar storms as predictable as hurricanes. To do that, scientists must create a model of space weather covering the more than ninety million miles between the sun's surface and the Earth's atmosphere. With five years of funding remaining, getting the job done will take the cooperation of astronomers, physicists, and computational scientists from BU and across the country. CISM's challenge isn't just to build a model; it's to create something that both faithfully mimics space weather in the lab and is effective, fast, and reliable when real solar storms threaten.

"Many people have said it wasn't worth trying to model the whole sun-to-Earth system, that we didn't understand it well enough," Hughes says. "Well, this is the experiment. Can we establish that it is worthwhile, or are those people right?"

PHOTO BY VERNON DOUCETTE

"WE NEED TO UNDERSTAND THE RULES MOTHER NATURE HAS GIVEN US."

— JACK QUINN,
COLLEGE OF ARTS AND SCIENCES
RESEARCH PROFESSOR OF ASTRONOMY

THREATS FROM ABOVE

In September 1859, telegraph service shorted out in the United States and in Europe. NASA researchers have since pinned the blame on a major solar storm, the earliest record of space weather affecting Earth-based communications. Since then, solar storms have caused incidents ranging from radar blackouts in World War II to a 1958 disruption in transatlantic phone service. NASA's Johnson Space Center began monitoring space weather in 1962 to assist the Apollo missions, which would eventually land men on the moon.

These days, space is no longer the domain of just astronomers and mission control. "All sorts of people on the ground now rely on satellite communications, ranging from farmers using GPS to monitor their crops and position irrigation and fertilizer to people moving big oil platforms around the Gulf of Mexico," says Quinn.

Consider this: in 2007 alone, fifty years after Sputnik, about 100 satellites were launched, joining nearly 1,000 already orbiting our planet. Many are used for scientific research or by the military, but their commercial uses are multiplying. About sixteen million people now subscribe to satellite radio, and between 2000 and 2005, annual sales of GPS more than doubled, to about $20 billion, according to industry research. Wireless communication devices, such as cell phones and the radio-frequency identification tags that track products worldwide, are nearly ubiquitous and are increasingly networked via satellite.

All of these communications and media systems are vulnerable to solar storms, particularly coronal mass ejections (CMEs), the shock waves of solar plasma made up of charged protons and electrons. CMEs can slam into the Earth's magnetosphere in less than a day and cause huge geomagnetic disturbances that can knock out satellites and overload electric power grids.

In 1989, space weather caused power blackouts for millions in Quebec and the northeastern United States, frying transformers and requiring about $1.2 billion in repairs and upgrades. Less than a decade later, a space weather event disrupted pager service to forty-five million Americans, about 80 percent of all subscribers.