FORECASTING SPACE WEATHER AT THE EARTH AND BEYOND

Space Weather

The terms "space weather" and "space climate" were coined not long ago to describe current and time-averaged conditions in the Earth's outer *environment*, in the same way that "weather" and "climate" refer to current or time-averaged conditions in the lower atmosphere. Space weather includes any and all conditions and events on the Sun, in the solar wind, in near-Earth space and in our upper atmosphere that can affect space-borne and ground-based technological systems and through these, human life and endeavor.

As noted earlier, the economic impacts of severe space weather events—such as the major electric power outages that can follow strong geomagnetic storms, or the disabling effects of solar eruptions on costly spacecraft—can easily reach the level of direct and indirect losses now associated with the most severe weather phenomena. Even moderate space weather events can affect national security, and in many ways. Extreme space weather events can very seriously also affect human life and health on extended lunar or planetary missions of exploration.

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Terrestrial weather has long been of interest and concern to everyone on Earth. But in the modern, interconnected high-tech world of today, *space* weather is fast becoming equally important and down-to-earth. Today it can affect anyone who has a television set, a radio, or a computer, or who makes use of GPS in any way; all who travel on jet aircraft flights that cross high-latitude regions in either hemisphere; nearly every city, large or small, that is linked to an electric power grid; every ship afloat; every spacecraft that is sent into the sky; and any nation whose security rests in part or all on radio communications, radar, or space-borne equipment.

In predicting day-to-day *weather* the volume of space in which measurements are taken and predictive models are run is limited to the troposphere: a thin veneer of air extending no more than about seven miles above the surface of the Earth.

In contrast, the vast domain of space weather and space climate starts in the upper atmosphere—about fifty miles above our heads, and reaches all the way to the Sun itself: nearly 100 million miles away. Within this vast region of interest are the ionosphere, thermosphere, magnetosphere and radiation belts; the immense volume of interplanetary space through which high-energy solar and cosmic particles pass to reach the Earth; the Moon and the inner planets, and the fiery furnace of the Sun itself.

Predictions

We have little if any control over the weather, and none at all over space weather events. But we can minimize the societal impacts of variations in either of them through reliable predictions of what is expected—or not expected—at any time.

Forecasts of the next day's weather at any place customarily include high and low air temperatures, precipitation, cloud cover, expected winds, and other meteorological parameters derived from computerized models of atmospheric circulation at different heights in the troposphere. The data needed to supply these models come largely from *in situ* measurements and observations obtained from a shared, world-wide network of weather stations; from balloon sondes; and since 1975—when the first *Observational Environmental Satellite (GOES-1)* was put into orbit—from direct, large-scale pictures of cloud cover and storm tracks seen from a height of 22,200 miles.

Information regarding space weather is obtained in much the same way, as are corresponding three-day or longer forecasts of things to come.

Among the need-to-know users of reliable *space weather* information are commercial airlines; electric power companies; almost every segment of the telecommunications industry including cell-phone and GPS providers; law enforcement; homeland security; banking and other commercial interests; those who go down to the sea in ships; all branches of the military; NASA and other national or international space agencies, particularly at times of human or robotic exploration; and commercial space and space tourism ventures.

Meeting the specific needs of these and other users often calls for tailored "predictions" of various kinds, all of them based in large part on computerized models that reproduce the behavior of parts or all of the Sun-Earth system.

The most common prediction is a "forecast": a prediction issued before an event such as flare or geomagnetic storm takes place. An example is the arrival of a fast moving CME, or a severe magnetic storm. But there are useful predictions of other kinds.

A "nowcast," as in meteorology, is a statement of current conditions at this time. Actual "predictions" may be in the form of an "alert," which might state, for example, that *A large fast-moving CME appears at this time to be headed toward the Earth;* a "watch" telling for example whether it is likely (or unlikely) that the present very low or very high level of solar activity will persist through the next two weeks; or a "warning" such as *Major disruptions in the ionosphere are expected during the next eight to ten days, in connection with expected CME and flare activity.*

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In the past, warnings of unfavorable weather and impending storms on land or sea were often issued using color-coded lights or flags, not unlike the red-orange-yellow advisories that were a few years ago tried to signal different levels of perceived homeland security risk.

In Birmingham, Alabama for example, a continuously-burning electric beacon was for many years employed to alert residents of potentially hazardous driving conditions. The warning light—installed where all could see it, atop an iron statue of Vulcan, 55 ft. tall and set on a high pedestal at the summit of Red Mountain—burned *green* for "all clear" or *red* when a fatal traffic accident had occurred.

Simple warning systems of a similar nature employing displays of colored flags and lanterns were and are still used in marinas, harbors and many coastal points to advise mariners or recreational sailors of expected hurricanes and other severe storm conditions.

Today and around the world, warnings of severe weather—at sea, on land, or in space—are broadcast or disseminated electronically and instantly to anyone concerned; and in more detail, which is required to serve the specific and often tailored needs of the many different users of this information. This is particularly true in space weather, where needless to say, a simple color-coded alert system—perhaps *red* to indicate that solar or geomagnetic storms are expected, *green* that they are not, and *orange* and *yellow* for different degrees of ambiguity—would not be of much use in this case, either.

USEFUL SPACE WEATHER PREDICTION

THE SUN

- Probability, magnitude and expected duration of solar flares
- Probability, size, speed and direction of CMEs
- Probability and nature of solar energetic particle (SEP) events
- 27-day or longer forecasts of solar conditions

INTERPLANETARY AND NEAR-EARTH ENVIRONMENT

- Intensity of solar EUV irradiation
- Particle radiation environment in near-Earth space
- Solar wind plasma parameters: density, velocity and magnetic field orientation
- Trajectories, predicted arrival time and likely impact of CMEs
- Cosmic ray flux level

MAGNETOSPHERE AND RADIATION BELTS

- Expected conditions in the magnetosphere and radiation belts
- Strengths of electric current systems in the magnetosphere
- Expected geomagnetic storms including onset, intensity, and duration
- Ground induced currents

UPPER AND LOWER ATMOSPHERE

- Conditions in the thermosphere and ionosphere
- Onset, intensity and expected recovery of ionospheric storms
- High energy particle fluxes at jet aircraft altitudes

Sources of Needed Data

In some instances the information needed for an accurate space weather forecast are secured—as in meteorology—by direct, *in situ* sampling. Examples are data regarding the composition, energy and magnetic field orientation of the solar wind plasma, sampled when possible by spacecraft that are at the time immersed in that medium. Another is the continuous record of characteristics of the Earth's magnetic field recorded by magnetometers through a global network of ground-level stations. A third is *in situ* measurements of the ambient flux of high-energy particles sensed by the radiation counters routinely carried for determining the dosage of ionizing radiation received on some European airlines.

But most of the data that provide current information about the Sun, cosmic rays, the magnetosphere and plasmasphere, and the thermosphere and ionosphere are arrived at indirectly, or observed from afar by remote sensing.

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Information regarding the Sun comes chiefly from telescopic observations made either on the ground or by spacecraft above the atmosphere. Images of the corona, needed for the prediction and monitoring of CMEs come mostly from space-borne x-ray telescopes and visible-light coronagraphs. The total and spectral irradiance received from the Sun—from the x-ray and EUV to the infrared—is also continuously monitored from afar by space-borne radiometers designed to secure these critical data from above the interfering atmosphere.

The flux of solar EUV radiation obtained from solar-pointed spacecraft is a particularly vital source of information because of its role in configuring the layered ionosphere, and heating the thermosphere. Estimates of the flux of solar EUV irradiation—and its variation from minute to minute or year to year—are also obtained, though less directly, from ground-based solar radio telescopes that monitor the intensity and variability of coronal radio emission. Ground-based measurements of the radiation of the unresolved disk of the Sun in two narrow spectral lines—that of ionized calcium in the near-ultraviolet and helium in the near-infrared—provide other proxies for the whole-disk solar EUV radiation.

When solar radio antennas are pointed at the Sun and their receivers tuned to 2.80 gigahertz (10.7 cm wavelength) in the ultra-high frequency band, they receive solar radio emission that comes from the same level in the Sun's outer atmosphere that produces energetic solar EUV radiation. Because of this, records of solar radio emission at this wavelength and of whole-disk EUV radiation closely track each other.

Like measurements from space of the total solar irradiance in the EUV, 10.7 cm radio emission from the Sun records the *averaged* radiation from the entire visible disk, without spatially resolving individual bright or dark features: as though the Sun were a star-like dot in the sky. Because of this built-in averaging, measurements of 10.7 cm solar radio emission have since the 1950s provided an alternate spatially-averaged index of solar activity that complements the daily sunspot number.

Of these two, the 10.7 cm radio index is less subjective than the venerable sunspot number, which was arbitrarily defined by Rudolph Wolf in Zürich in 1849 as the number of discernible spots seen on the disk plus ten times the number of sunspot groups, all multiplied by an estimated correction factor to compensate for perceived differences in observers, telescopes, observing sites and atmospheric conditions.

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An indirect measure of the flux of galactic cosmic rays at the top of the Earth's atmosphere is provided by neutron monitors operated at high-altitude stations around the world. The numbers of neutrons that penetrate to these lower levels is at any time a proxy indicator of the incidence of primary cosmic rays higher in the atmosphere, which through collisions with atoms and molecules of air produce these most energetic secondary cosmic ray particles.

The density of electrons in different layers of the ionosphere—the determining factor in forecasts of radio propagation conditions—is also recovered indirectly by remote sensing, in this case employing radio waves transmitted upward from the ground. As in conventional radar, the strength and timing of the reflected signal can be read in terms of the local structure and electron density in the layered atmosphere, fifty to several hundred miles overhead.

Available Warning Times

The extreme speeds at which energetic solar particles and radiation stream outward from the Sun impose severe limits on the amount of time available, once an event is observed there, to react to or mitigate its possible effects.

All electromagnetic radiation leaves the Sun at the same velocity—the speed of light, about 186,000 miles per second—and reaches the Earth in eight minutes. The speeds of atomic *particles* depend upon their own energy, at the Sun and en route.

Slow-speed streams in the solar wind can take more than four days to make the journey, while solar energetic protons (SEPs) can arrive in a matter of tens of minutes or less. Less energetic particles from the Sun, and those carried outward in CMEs, generally arrive at the orbit of the Earth in from one to three days.

But the warning time available to us on Earth is always eight minutes less than the time it takes particles or photons to get here.

This automatic deduction is a consequence of the fact that what we see when we look at the Sun is not what is happening at this minute, but what happened there eight minutes ago: the time it takes visible light to travel the 93 million miles that separate us from the star. Were we on Mars, a look at the Sun would show us what it was like there about 12 minutes before; and on Jupiter, almost three quarters of an hour ago.

TRAVEL TIME FROM THE SUN TO THE EARTH

PARTICLES	**SPEED IN MILES/ SEC**	**TIME TO REACH THE EARTH**
Particles in the slow solar wind	250	4½ days
Particles in a typical CME	250	4½ days
Particles in high-speed streams	470	2½ days
Less energetic particles from solar flares	360 to 1100	1 to 3 days
Particles in the fastest CMEs	1200	30 minutes to several hours
Energetic protons from solar flares	25,000 to 100,000	15-60 minutes
ELECTROMAGNETIC RADIATION		
X-ray, EUV, UV, Visible, Infrared, and Radio radiation	186,000	8 minutes

Thus the moment we first see the bright flash of a solar flare, the energetic EUV and x-ray radiation it sends our way has already arrived—as though it got here instantly; and the damaging high energy protons that can travel to the Earth in but 15 minutes time are already more than halfway here, leaving us at most but seven minutes' warning time. For most other particles—including the fastest plasma in CMEs, the obligatory eight-minute deduction is not as significant.

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How much warning time is needed to mitigate possible deleterious effects at the Earth?

An hour of advanced warning of a severe geomagnetic storm can be helpful for electric power companies, for in that time they can change the way they generate and distribute energy. An hour or less may be enough to allow air controllers to reduce the altitude of flights passing through polar regions or to redirect the flight paths of those en route. A half hour to an hour *may* be enough for astronauts engaged in extravehicular activity to scurry back inside, or for those on the surface of the Moon or Mars to seek shelter—if there is any—from an anticipated burst of extremely energetic particles from the Sun.

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There are also ways of gaining more warning time.

One is to delay the mission itself if unusual solar activity is expected, or to postpone scheduled space walks en route to or on the surface of the Moon or Mars. Another is to direct crews to hunker down in parts of the command module, or if space allows, in the lunar lander that may in places offer marginal protection.

The most beneficial and challenging way to increase the warning time is through reliable predictions of when and where likely solar eruptive events will occur. For CMEs, the prediction must reliably foretell whether the expanding blob of plasma will cross the Earth's path. If so, its size and speed and the orientation of the magnetic field it carries are also needed, as is its projected time of arrival and the probability of intense geomagnetic storms.

Alerts and warnings must first of all be reliable, since in many applications false alarms can lead to considerable unnecessary expense. Examples are electric power companies who will reconfigure power distribution networks or put on extra equipment in anticipation of a major geomagnetic storm; airlines who will expend additional fuel and delay or cancel flights; telecommunications carriers who will shift frequencies and strategies. False alarms can also limit the accomplishments and ultimate success of costly space missions when tightly-scheduled activities are cancelled, or result in a depletion of orbital control fuel.

Assistance in increasing the accuracy and the warning time of forecasts is now available thanks to the deployment of early-warning spacecraft that are stationed, like sentinels, nearer to the Sun than we. In these advanced positions they can send back vital information, as from scouts sent ahead of an advancing troop of the U.S. Cavalry.

Radioed early warnings sent back to us from distant sentinels can never outrun the x-ray and EUV photons that race past them, traveling at the speed of light toward the Earth. But they will get here well in advance of approaching CMEs, fast streams in the solar wind, and most energetic particles coming from flares.

The *ACE* spacecraft, launched in 1997 and still hard at work, was designed to study the composition of plasma and energetic particles in the heliosphere from a distant outpost nearly a million miles closer to the Sun than we, where it serves as a watchman or sentinel of this kind.

Especial Needs for Manned Space Exploration

Streams of solar protons and heavier ions with particle energies in the range of 10^6 to 10^9 electron volts can pose severe hazards for manned space missions that venture beyond the natural protection of the Earth's atmosphere and magnetosphere. Continuous exposure to galactic cosmic rays, with even higher energies is equally if not more hazardous to manned space flight. Exposure to sufficient doses of the ionizing radiation of highly-energetic atomic particles can damage cells in living tissue and organs that provoke cellular mutations and incipient cancer; induce nausea and the debilitating symptoms of radiation sickness that were felt by victims of atomic bomb explosions sixty years ago; and lead to slow or sudden death.

At the same time, each high-energy atomic particle that streams through our bodies is not a deadly bullet. Nor is it likely that a single burst or stream of them would be.

The critical factor—for astronauts, pilots, passengers, or patients in a dentist's chair—is, as noted earlier, the *accumulated dosage* that one receives: the product of the *intensity* of the ionizing radiation (determined by the speed, mass, and number of ionizing particles) and the amount of time one is exposed to it.

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Every manned spacecraft that ventures beyond the Earth's atmosphere and magnetosphere will find itself caught in the crossfire of energetic particles coming from as many as four different sources.

The first and least hazardous is the ubiquitous solar wind in which spacecraft are immersed as soon as they leave the protective shields that surround the Earth: the ever present flow of low energy (1 – 10 keV) particles borne outward from the Sun in a turbulent mix of steady breezes and sudden gusts. Immensely more energetic cosmic rays are also ever present, arriving from every direction in the sky and able to pierce almost anything.

A spaceship in deep space will at times also find itself directly in the path of fast-moving CMEs: but these particles, too, are limited to the low energy range of a few KeV and are not ordinarily a direct threat to space travel.

The least frequent but probably most hazardous to life and health are the solar energetic protons (SEPs) and heavier ions that are accelerated outward by CMEs and major solar flares, and in the shock waves that form—like the bow wave of a ship—some distance ahead of the fast-moving plasma. These travel toward us at almost unimaginable velocities which can approach the speed of light. When coupled with their appreciable mass, this makes SEPs, with cosmic rays, the principal threats to be avoided in manned space flight. And they can rain down on our planet, on the Moon and Mars and in near-Earth space for hours on end.

The challenge in deep-space exploration of the Moon and Mars is to provide shielding sufficient to block or deter any of these ultra-high-energy particles from reaching parts of the spacecraft where astronauts live, work or seek shelter.

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It has been estimated that astronauts on extended trips like those envisioned for Mars or for manned colonies on the Moon would each year receive from galactic cosmic rays fully 16 times the maximum authorized dose of ionizing radiation prescribed for nuclear plant workers. Moreover, to be effectively shielded from GCRs while on the surface of either body would require burying a lunar or Martian base below hundreds of tons of lunar or Martian soil.

Sunset at the close of a Martian day seen from the Mars Pathfinder on the planet's surface. With a much thinner atmosphere—evident here in the absence of sunset colors—almost no UV-absorbing oxygen, and no magnetic field, visitors on the planet will be exposed to the hazards of solar x-ray and extreme-ultraviolet radiation, bursts of energetic solar particles, and the round-the-clock barrage of extremely energetic cosmic rays.

As noted earlier, a 100 MeV proton can easily pass through an inch and a half of aluminum, and cosmic ray particles can be orders of magnitude more energetic than that. It is therefore likely that the metal skin and frame of the command service modules and lunar landers that were sent on *Apollo* missions to the Moon in the 1960s and 1970s would have provided little if any protection against these most energetic atomic particles.

Galactic cosmic rays, as noted above, pose difficult problems for extended manned missions since they are more energetic and are present all of the time. The greatest challenge is the accumulated dosage of GCRs encountered on long space flights, such as the deep-space missions, two or three years long, that have been envisioned for the manned exploration of Mars. On missions of this duration, the accumulated dosage of galactic cosmic rays would almost surely exceed the threat from solar flares and CMEs. Indeed, cosmic rays may indeed be a show-stopper for manned missions to Mars unless practical ways are found to provide effective shielding against them.

PRINCIPAL HAZARDS OF HUMAN SPACE FLIGHT ON MISSIONS THAT TRAVEL BEYOND THE EARTH'S ATMOSPHERE AND MAGNETOSPHERE

SOURCE	ENERGY PER PARTICLE IN ELECTRON VOLTS	MOST PROBABLE TIME OF OCCURRENCE; AND EXPECTED EXPOSURE	PRINCIPAL CONCERN
SOLAR ENERGETIC PARTICLES from major solar flares and CME-driven shock waves	10^6 - 10^9	During periods of high solar activity, which are more likely during or following maximum years of the eleven yr cycle --------------. 30 minutes to several days for those associated with observed CMEs	Persistent or repeated exposure to unusually intense events
GALACTIC COSMIC RAYS	10^9 - 10^{20}	Continuous	Accumulated dosage on space missions lasting longer than a few days or weeks

Current Capabilities

The ultimate goal in studying space weather is an ability to foretell events and conditions on the Sun and in near-Earth space that will produce potentially harmful societal effects, and to do this adequately far in advance and with sufficient accuracy to allow preventive or mitigating actions to be taken. In this sense it is much like the goal of predicting earthquakes or tsunamis, or more appropriately, the daily tasks of today's National Weather Service, but for a region that is 10^{14} times larger: namely, the volume of space that includes the Sun, the Earth, the Moon and ultimately, Mars.

Our ability to attempt forecasts of this kind rests on the foundation of a long history of accomplishments in research, discovery and investigation; on the daily operation of solar and magnetic observatories around the world; on the launch and operation of a growing number of spacecraft designed to meet this need; on the development and continual improvement of analytical models of parts or all of the Sun-Earth system; and on a national and international infrastructure which has helped organize and sustain these global efforts for the common good.

In our own country, the interagency framework which can help meet this challenge has been provided since 1995 by the National Space Weather Program (NSWP) which was organized to ensure collaborative efforts among seven federal agencies that had individually addressed or were significantly affected by space weather. Included are NASA; the National Science Foundation; the

National Oceanic and Atmospheric Administration (NOAA, through the Department of Commerce); the Department of Defense; and the Departments of Energy, Transportation, and the Interior.

Operational Facilities

There are two civilian operational organizations that in this country process and interpret space weather information to provide forecasts and real-time warnings of space weather disturbances for specific users of this information.

The first and more specifically relevant to the needs of human space flight is the Space Radiation Analysis Group (SRAG) operated at the Johnson Space Center in Houston, Texas by NASA's Radiation Health Program: an arm of the Agency that has long tracked and studied the potentially harmful impacts of high-energy, ionizing radiation from the Sun or the Cosmos on human space travelers.

The second addresses impacts of space weather on the broader community of those affected by it, from aircraft operations to communications and electric power systems and geophysical exploration. It is known as the Space Weather Prediction Center, or SWPC, a world solar and space weather monitoring center operated in Boulder, Colorado through the joint efforts of NOAA and the U.S. Air Force.

Each of these two dedicated centers keeps a twenty-four hours a day, seven days a week watch on the Sun and near-Earth space. Each is staffed by trained professionals and function much like Combat Information Centers on ships of war, or the Situation Rooms that somewhere deep within the White House or the Pentagon track national security happenings as they unfold.

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Is more than one operational space weather patrol necessary? Are two policemen or two firemen better than one? The SRAG and SWPC serve two quite different communities and focus on two separate and urgent needs, and through essential overlap provide enhanced scrutiny and back-up. Each keeps a round-the-clock watch on the face of the Sun, its surface magnetic fields and its outer atmosphere, tracks the birth and development of individual solar active regions, and monitors conditions in near-Earth space. Working cooperatively, they keep a close eye on solar magnetic regions that are likely to erupt in flares and produce CMEs, and track their progress with these eventualities in mind. In the same way they follow the evolution of active prominences and watch for ominous changes in the inner and outer corona, identify CMEs as they first appear, project their outward progress and for those headed in our direction, forecast their time of arrival and expected impacts.

In order to do this, the SRAG and SWPC receive continuous flows of information from solar and magnetic observatories around the world, following the path of a Sun that never sets, as well as data from dedicated spacecraft that continually watch the inner corona in the light of its short-wavelength emission, and with space-borne white-light coronagraphs, the changing form of the outer corona.

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The SRAG at the Johnson Space Center is responsible for ensuring that the dosage of ionizing radiation received by astronauts from solar eruptions and galactic cosmic rays remains below established safety limits. To do this the activity provides

- continual monitoring of space weather conditions, including information from instruments on board operational satellites such as GOES, SOHO and ACE;
- comprehensive advance and real-time information on radiological exposure during specific manned missions;
- monitoring equipment carried on board to measure the actual radiation environment inside and outside the spacecraft
- extra-vehicular activity (EVA) planning, support and monitoring;
- advance information and updates to mission planners, flight controllers, flight directors and flight surgeons on expected solar behavior and radiation levels;
- contingency responses to likely space weather events during specific missions;
- pre-flight modeling of expected crew exposure, particularly during EVAs;
- evaluation of radiological safety from exposure to radiation-producing equipment on the spacecraft itself;
- tracking of the daily and cumulative doses of radiation received by each member of the spacecraft crew; and
- an interface with support groups within and outside the agency, including the SWPC.

An appreciation of the level of effort and expertise devoted to these challenges at the SRAG can be gained very quickly by logging on to its web site, http://srag-nt.jsc.nasa.gov/. Included there, as well, is a trove of summarized information on space shuttle missions currently planned or in progress and the current status of the International Space Station.

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Additional streams of incoming information allow the SWPC in Boulder to track conditions in the approaching solar wind and the flow of particles at the top of the Earth's atmosphere that foretell the occurrence of magnetic storms and auroral displays. Other data tell of the changing state of the magnetosphere and the electric currents that flow within it, and of conditions in the thermosphere and layered ionosphere.

Based on an assimilation and considered interpretation of all these data, and aided by analytical models, a day-by-day forecast is prepared for space weather conditions in the next three days.

Among the many users of these current reports of vital information are the Federal Aviation Agency; the Departments of Defense and Homeland Security; NASA, providing a supplemental flow of information throughout the full duration of crewed space missions; the U.S. Nuclear Regulatory Commission and electric power industry in anticipation of possible power interruptions; those involved in geological surveys and exploration; and the many others—including particularly the operators of satellite communications and navigation systems and the broadcast industry—who depend upon reliable and uninterrupted telecommunications. All of the general projections and the background information on which they are based are made immediately available to the whole wide world on the internet (see, for example, http://www.swpc.noaa.gov/)

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Nearly every impending solar-driven storm—and all of the largest and most threatening—can be foreseen with the advantages of 24-hour observations of the Sun, the considerable help of early warnings from the distant ACE spacecraft and improved understanding of the chain of events that connect solar disturbances to the Earth.

One of the most taxing challenges facing the SWPC and SRAG is an accurate and precise prediction of the date and time of arrival at the Earth, the Moon or Mars, of the particles and fields that are driven outward from these very distant events. A decade ago specific predictions for the Earth were correct about a third of the time. Today the batting average is about .500, which is about the same as was the case with the prediction of severe meteorological storms—then a more mature field of study—in the 1960s.

Advance alerts and warnings issued from the SWPC were instrumental in mitigating the possible impacts from what became known as the "Great Bastille Day flare" of July 14, 2000: a long-lasting release of magnetic energy from the Sun that was followed by three fast-traveling shock waves and the immediate discharge of a monstrous CME that was directed, like a huge cannon ball, precisely at the Earth. When it hit, the momentum of the CME pushed the Sun-facing side of the magnetosphere so close to the Earth that spacecraft in geosynchronous orbits, normally shielded by the magnetosphere, were left, fully exposed, outside it. The SWPC in Boulder proved its worth again with highly useful predictions of what came to be called "the Halloween Day" storms in late October, 2003: another awesome display of solar eruptions and terrestrial effects that were released by the Sun two years after the peak of the most recent solar cycle.

Even the early warning ACE spacecraft was so showered with particles in this event that it ceased to operate for a time. By the next day the largest magnetic storm in eleven years had perturbed the upper atmosphere all around the Earth, setting off low-latitude displays of the aurora borealis and australis.

Probably the most threatening impacts on the surface of the Earth were the effects of unusually strong induced electric currents on power distribution systems that damaged power transformers at twelve power plants in North America. But in this case alerts that were issued by the SWPC in advance of the geomagnetic storm allowed time for power companies—including nuclear power plants—to prepare for the event. As a result there were neither blackouts nor major financial impacts.

The Heliophysics System Observatory

Some twenty-six operational spacecraft circling both the Earth and the Sun—or on further voyages of discovery, far from home—now explore, patrol and monitor the complex, coupled Sun-Earth system. They are there to identify, understand and ultimately predict the major changes on the Sun and in near-Earth space that affect space weather and human endeavor. To do this they are designed and operated to complement each other, and to work together as an ongoing System Observatory in near-Earth space.

NASA develops this bold system as an evolving entity, responding to practical needs, new findings and the necessity to replace ailing or failed elements. Long lead-times are involved in the initial concept and design, operational plan, funding, construction, testing and launch of any new spacecraft. Thus, in order to meet anticipated needs of the System Observatory in this and future

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decades there are now more than forty other spacecraft at various stages of development—from initial concept to fully funded and under construction—working their way through this long pipeline.

Ships in this potential fleet, like those now in operation, differ in many ways, including (1) their specific mission, and the instruments they carry to accomplish it; (2) their size, weight, scope, anticipated lifetime and expected time of delivery; (3) the nature and complexity of their envisioned operation, including their orbit (or orbits where multiple spacecraft are involved) and the proposed scheme of in-flight control and data management; and (4) their method of launch, and often-shared sources of support, within this country or abroad. These parameters all bear on the cost of the proposed mission.

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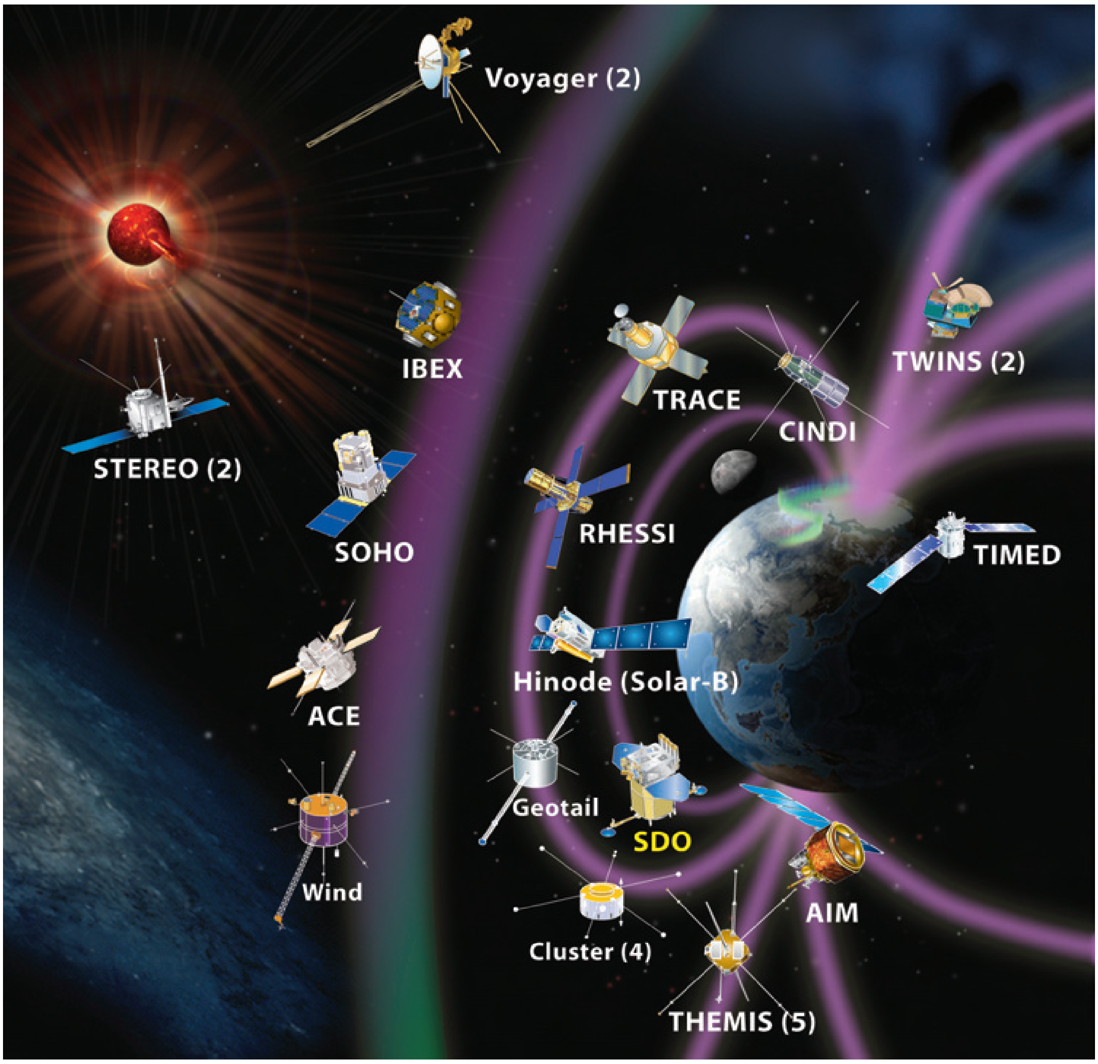
Spacecraft of the System Observatory that are currently in operation—or expected to join the fleet by the end of year 2009—are briefly described in the accompanying table, where they are listed in order of launch date and separated by color code into three broad areas of principal emphasis within the Sun-Earth system.



The evolving Heliophysics System Observatory consisting of current and some future spacecraft that study the Sun and the Sun-Earth environment. Currently operating spacecraft missions as of July 2009 appear in white, future scheduled launches in yellow.

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SPACECRAFT THAT NOW STUDY AND MONITOR THE SUN-EARTH SYSTEM

Principal emphasis:
Sun and heliosphere
Solar wind particles and fields
Magnetosphere and upper atmosphere

SPACECRAFT	DATE LAUNCHED	ORBIT	MISSION
VOYAGERS 1 and 2 *NASA*	1977	Outward journey from the Earth and the Sun	Exploration of the outer boundary of the heliosphere
GEOTAIL *INSTITUTE OF SPACE AND ASTRONAUTICAL SCIENCE (ISAS) AND NASA*	1992	Highly elliptical orbit that takes it from 30 to about 200 R_E	Study of the dynamics of the Earth's magneto-tail
WIND *NASA*	1994	94,000 miles from the Earth at the L1 Lagrangian point	*In situ* study of the solar wind in a region closer to the Sun than we
SOHO (Solar and Heliospheric Observatory) *NASA, ESA*	1995	94,000 miles from the Earth at the L1 Lagrangian point	Observations and study of the solar interior, solar irradiance, solar magnetism and CMEs
ACE (Advanced Composition Explorer) *NASA*	1997	94,000 miles from the Earth at the L1 Lagrangian point	*In situ* measurements of the solar wind before it reaches the Earth
TRACE (Transition Region and Corona Explorer) *NASA*	1998	Circular, Sun-synchronous orbit around the Earth	Images of magnetic structures in the corona and transition zone
CLUSTER *EUROPEAN SPACE AGENCY (ESA) AND NASA*	2000	Four spacecraft in elliptical polar orbits, 12,000 to 74,000 miles above the surface	Investigation of critical phenomena in the magnetosphere
TIMED (Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics) *NASA*	2001	390-mile equatorial circular orbit around the Earth	Study of the coupled magnetosphere, thermosphere and ionosphere
RHESSI (Reuven Ramaty High Energy Solar Spectroscopic Imager) *NASA*	2002	370-mile Sun-synchronous circular orbit	Study of particle acceleration and energy release in the solar corona and flares

SPACECRAFT THAT NOW STUDY AND MONITOR THE SUN-EARTH SYSTEM (Continued)

Principal emphasis:
Sun and heliosphere
Solar wind particles and fields
Magnetosphere and upper atmosphere

SPACECRAFT	DATE LAUNCHED	ORBIT	MISSION
AIM (Aeronomy of Ice in the Mesosphere) *NASA*	2007	375 mile Sun-synchronous orbit	Radiometry and images of polar mesospheric clouds; linkages between vertical atmospheric regions
CINDI (Coupled Ion Neutral DYnamics Investigation) *U.S. AIR FORCE AND NASA*	2008	Equatorial circular orbit within the ionosphere	Measurements of irregularities in the ionospheric plasma as these pertain to radio propagation
HINODE (SOLAR-B) *AEROSPACE EXPLORATION AGENCY OF JAPAN (JAXA) AND NASA*	2006	370-mile Sun-synchronous circular orbit	Detailed observations and study of the evolution of solar magnetic fields
IBEX (Interstellar Boundary Explorer)	2008	High altitude orbit that reaches 150 thousand miles above the Earth	IBEX images will reveal global properties of the interstellar boundaries that separate our heliosphere from the local interstellar medium
STEREO *NASA*	2006	Two identical spacecraft in orbit about the Sun at 1 A.U.	3-dimensional observations of the Sun and CMEs
THEMIS (The History of Events and Macroscale Interactions during Substorms) *NASA*	2007	5 identical spacecraft in equatorial orbits at distances of 10 to 30 R_E	Particles and fields in the tail of the magnetosphere and their connections with magnetic substorms and aurorae
TWINS (Two Wide-angle Imaging Neutral-atom Spectrometers) *NASA*	2008	Two spacecraft, 29,000 miles above the Earth in high-inclination orbits	Stereoscopic imaging of the magnetosphere to study connections between processes in different regions

SPACECRAFT THAT WILL SOON STUDY AND MONITOR THE SUN-EARTH SYSTEM

SPACECRAFT	LAUNCH DATE	ORBIT	MISSION
SDO (Solar Dynamics Observatory) *NASA*	Fall 2009	22,200 miles above the Earth in an inclined geosynchronous orbit	Solar observations to clarify the sources of solar variability that affect life and society

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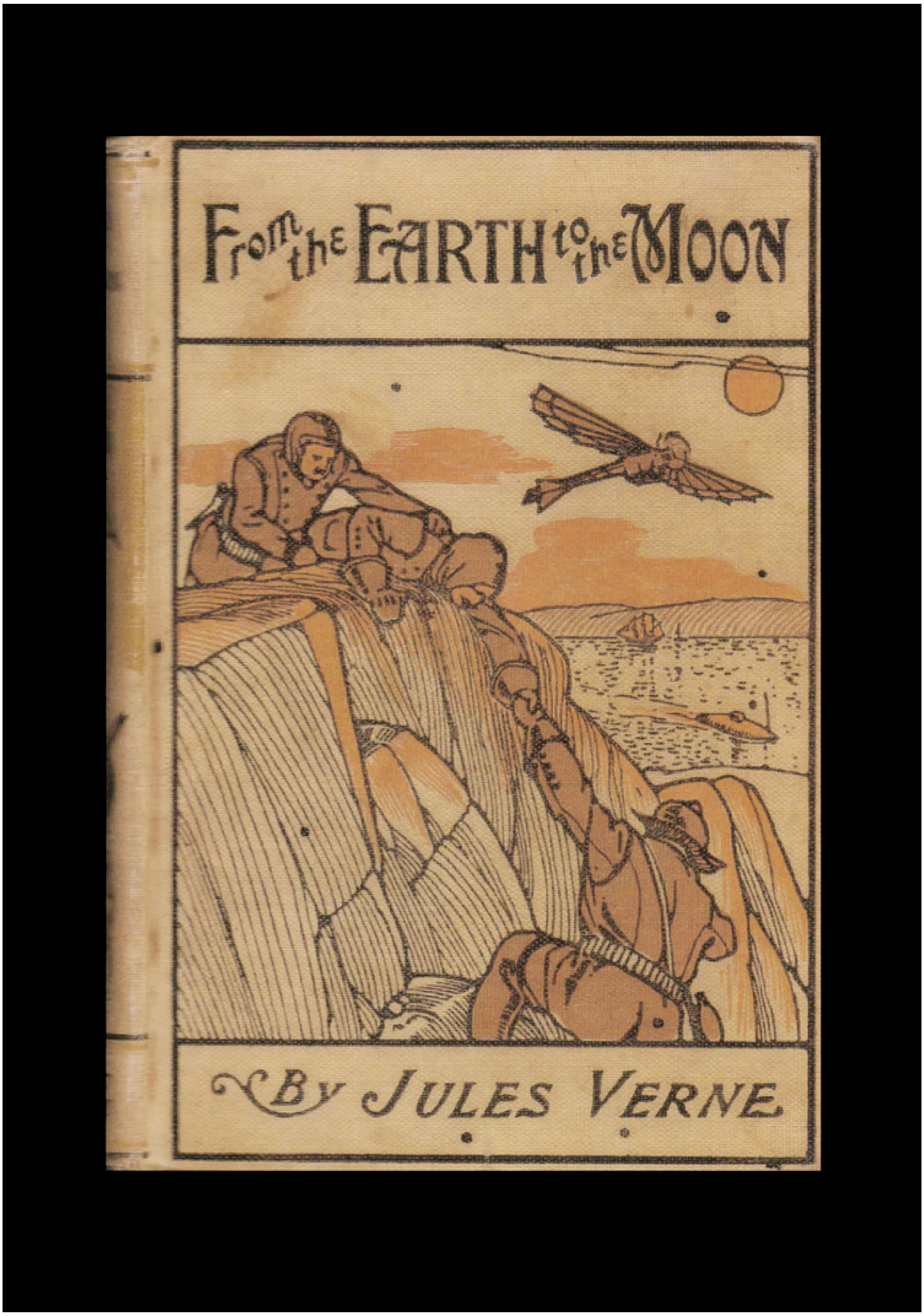
From the EARTH to the MOON
By JULES VERNE