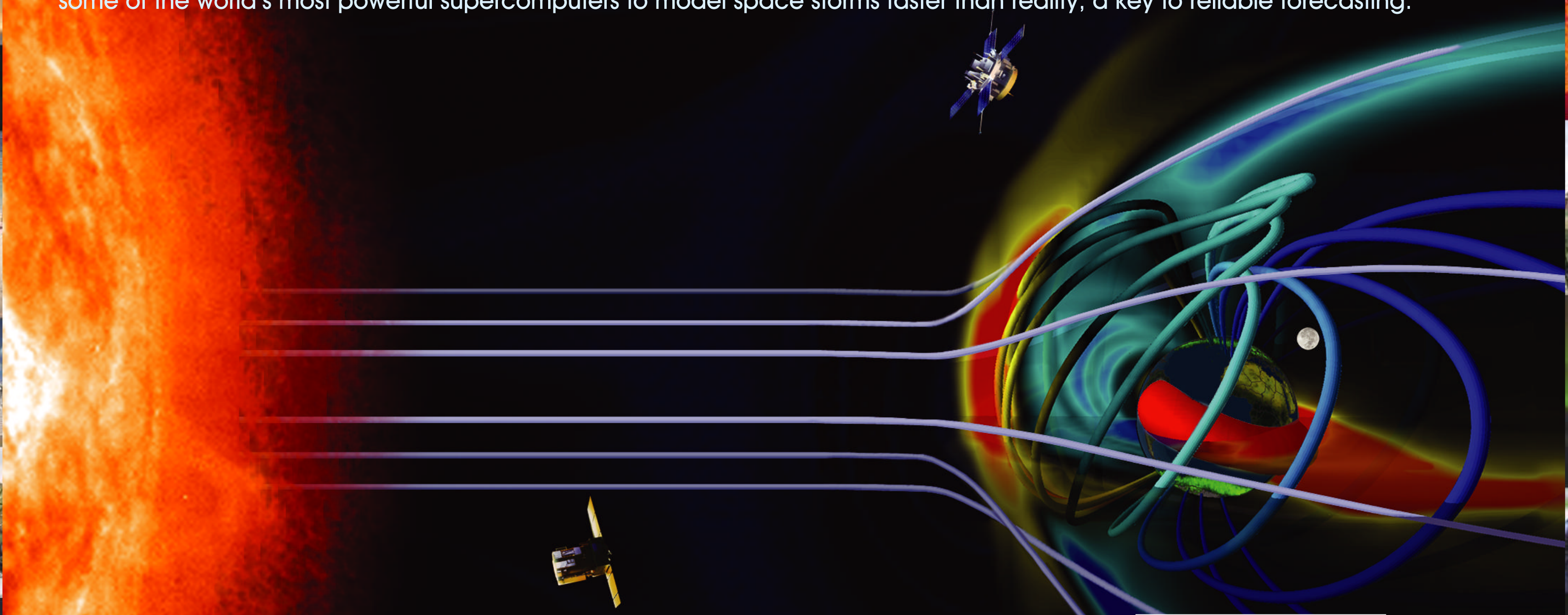
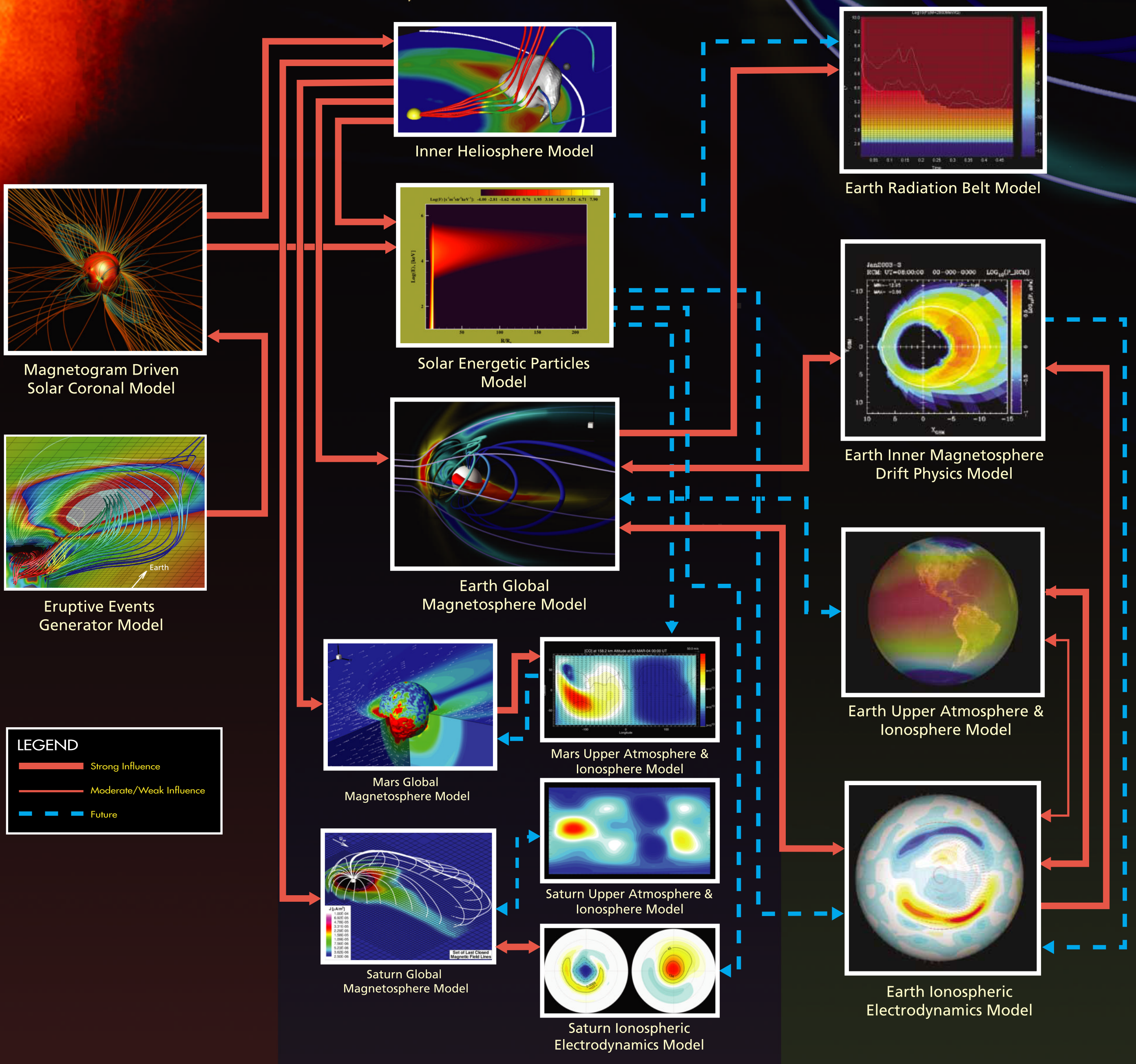
SWMF

SPACE WEATHER MODELING FRAMEWORK

Caused by magnetic and electrically charged phenomena traveling from our Sun, space weather affects life on Earth and our ability to explore the solar system. Space storms have created power outages, diverted airplanes, knocked out satellites, interrupted spacecraft communications, and forced astronauts to take cover.

To study and ultimately predict space weather, scientists are building a software tool called the Space Weather Modeling Framework (SWMF). By coupling a series of computer models, the SWMF can simulate space weather phenomena over vast regions of space — from the surface of the Sun to the upper atmosphere of Earth, the Moon, Mars, and beyond. The SWMF harnesses some of the world's most powerful supercomputers to model space storms faster than reality, a key to reliable forecasting.





Inner Heliosphere Model

Earth Radiation Belt Model

Magnetogram Driven Solar Coronal Model

Solar Energetic Particles Model

Earth Inner Magnetosphere Drift Physics Model

Eruptive Events Generator Model

Earth Global Magnetosphere Model

Earth Upper Atmosphere & Ionosphere Model

Mars Global Magnetosphere Model

Mars Upper Atmosphere & Ionosphere Model

Saturn Upper Atmosphere & Ionosphere Model

Earth Ionospheric Electrodynamics Model

Saturn Global Magnetosphere Model

Saturn Ionospheric Electrodynamics Model

LEGEND

▬ Strong Influence

— Moderate/Weak Influence

- - - Future

Solar

Interplanetary

Near-Earth

The Space Weather Modeling Framework (SWMF) is a software technology prototype being developed by the Computational Technologies Project, part of NASA's Earth-Sun System Technology Office.

http://ct.gsfc.nasa.gov

http://csem.engin.umich.edu

National Aeronautics and Space Administration
University of Michigan
National Science Foundation
United States Department of Defense

SPACE WEATHER MODELING FRAMEWORK

Confronting Monster Space Weather Events with Modeling

Three sunspots, including one the size of Jupiter, launch a series of solar eruptions. Among the 60 solar flares is the most intense ever observed, an X-28 flare accompanied by a coronal mass ejection (CME). In the CME, the Sun spews out several billion tons of matter at an astonishing 8 million kilometers per hour. Although this blob of charged gas does not hit the Earth, geomagnetic storms resulting from multiple Earth-bound flares and CMEs have widespread effects: Two satellites are knocked out of commission, and 28 more are damaged. Airlines divert their planes. Sweden suffers a power outage. Astronauts on the International Space Station have to take cover several times. The Northern Lights reach as far south as Florida.

The "Halloween 2003 space storms" began in late October and lasted through early November. This series of outbursts was the biggest solar event in recent history. NASA, the National Oceanic and Atmospheric Administration (NOAA), the U.S. Air Force, the U.S. Navy, and many other countries monitored the event. Indeed, a fleet of satellites observes daily solar activity in increasingly greater detail, giving scientists a better understanding of how the Sun works. From observations alone, however, they cannot forecast if and when solar storms will hit the Earth and what the effects will be. That task falls to simulations running on supercomputers capable of several trillion calculations per second.

A new simulation tool known as the Space Weather Modeling Framework (SWMF) is being applied to the Halloween 2003 space storms with an eye towards forecasting. The SWMF is a NASA Computational Technologies (CT) investigation based at the University of Michigan.

"With the help of the CT Project, we now have a fully operational framework with nine models working together," said SWMF principal investigator Tamas Gombosi, who is chair and professor of the Department of Atmospheric, Oceanic, and Space Sciences at Michigan. "This is the first time that we have exercised this brand new tool for a very challenging major event. It is a fortunate combination of simulation advances and the Sun cooperating in a very exciting way."

The SWMF has its origins in Michigan's BATS-R-US (Block Adaptive-Tree Solar-wind Roe-type Upwind Scheme) software developed under the CT Project (then known as the Earth and Space Sciences Project) beginning in 1996. Many of the SWMF models are considered world-class, Gombosi said, "but coupled together, they are better than the sum of their parts."

The Halloween 2003 storms are the first real application of the fully equipped SWMF. The Michigan team's Halloween 2003 simulation is a monster in its own right. "This is the biggest simulation we have done," Gombosi stressed. "No one has ever attempted such a simulation." To fully represent the Sun-Earth connection, SWMF must traverse 150 million kilometers of space, beginning 70,000 kilometers above the Sun's surface (the lower corona) and ending 100 kilometers above the Earth (the ionosphere).

Simulations divide space into a mesh containing millions of boxes and solve mathematical equations inside each box. To follow solar plasma, magnetic fields, and particles through space, the SWMF's boxes divide up to 15 times to cover scales down to 200 kilometers at the active region near the solar surface. Without this adaptive mesh refinement (AMR) technique, the simulation could not be run on today's supercomputers. Even with AMR, the high-resolution simulation is consuming 500,000 processor-hours on NASA's new Columbia supercomputer, an SGI Altix system at Ames Research Center in Moffett Field, CA. When linked together, Columbia's 10,240 processors can calculate over 50 trillion floating-point operations per second. With a highly scalable computer code, "we can run faster than real time with 1,000 processors," Gombosi said, which is a key requirement for producing forecasts. His group has run portions of the Halloween 2003 simulation. Using 508 processors, modeling the complete 30-day event is expected to take 40 days of computer time.

"One of the nice features of the SWMF is that we can run it with a limited number of components or the full component suite," said Aaron Ridley, associate research professor of space science at Michigan. "This allows a great deal of flexibility when attempting to conduct scientific research." To simulate the October 29, 2003 superstorm, the team ran the framework as two different systems, one focusing on the Sun and the other focusing on the Earth.

At the Sun, CME initiation is one of the most intensely studied areas. SWMF researchers are pushing the limits of computational power by resolving the structures that may be responsible for CME initiation. In attempting to realistically launch a CME into interplanetary space, they use a magnetic field configuration similar to that needed for the "break-out model." In this configuration, a magnetic loop confines the CME. At a null point within this magnetic loop, magnetic field lines can reconnect and free the CME to explode outwards.

At the Earth, the team ran simulations using upstream solar wind plasma and interplanetary magnetic field measured by NASA's Advanced Composition Explorer (ACE) satellite. One of the main focuses of SWMF development at Michigan has been verifying and validating the codes and the framework that binds them. The primary method has been to compare model data to observations from ground-based telescopes and orbiting spacecraft.

For example, the Dst index quantifies how intense the "ring current" is around the Earth. The ring current is formed when large electric fields build up in the magnetosphere, pushing particles towards the Earth. When these particles get close enough to the planet, they start drifting in different directions: the electrons go one way, and the high-energy ions go another way. This difference in the electron and ion flows causes a large current to form just inside of geosynchronous orbit, where many satellites travel. Comparisons of SWMF model output with Dst index values give the researchers confidence that the framework coupling is working as expected.

Satellites at geosynchronous orbit are subjected to all sorts of environments. "Normally these satellites sit in the Earth's dipolar field, with very little change in magnetic field strength," Ridley said. "During geomagnetic storms, though, these satellites can be bombarded by strong particle fluxes and sharply changing electric and magnetic fields." The SWMF team gathered magnetic field data from NOAA's GOES weather satellites, which are at geosynchronous orbit over the United States. During the Halloween 2003 space storms, the SWMF correctly predicted that two of the GOES satellites went outside of the magnetosphere, placing them in the open, potentially hostile solar wind environment.

Validating the Halloween 2003 simulations will help prepare the SWMF as a community tool. Michigan is transferring the software to NASA Goddard Space Flight Center's Community Coordinated Modeling Center in Greenbelt, MD, and NOAA's Space Environment Center in Boulder, CO. Researchers in these organizations will use SWMF software codes for operational solar and space weather forecasting as well as scientific analysis.

Space Weather Modeling Framework (SWMF) Component Models

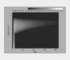
Solar

The Magnetogram Driven Solar Coronal Model represents the Sun's corona (atmosphere) using solar observation data. It is a 3D magnetohydrodynamics code in a rotating spherical coordinate system. The Coronal Model drives the solar wind and determines the open/closed field lines in a self-consistent way.

The Eruptive Events Generator Model inputs a coronal mass ejection into the initial conditions of the simulation. The mass ejection then propagates outward through the Solar Coronal and Inner Heliosphere models self-consistently. There are currently two different methods for initiating Eruptive Events, and progress is being made on a more physically realistic, dynamically evolving, self-consistent methodology for erupting coronal mass ejections.

Interplanetary

The Inner Heliosphere Model simulates the solar wind from the outer boundary of the corona to the Earth's magnetosphere and beyond, based on magnetohydrodynamics. This 3D Cartesian coordinate code is used to propagate events from the Sun to the Earth using adaptive mesh refinement, allowing for very high-resolution simulations of coronal mass ejections and other structures.

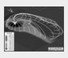


The Solar Energetic Particles Model describes the transport, acceleration, and scattering of these particles from the solar event to the Earth's atmosphere. It is a field-aligned code that uses dynamically changing field-lines to model the processes. The field-lines are traced from the Solar Coronal and Inner Heliosphere models.

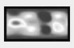
The Earth Global Magnetosphere Model describes the connection between the inner heliosphere and the outer portion of the Earth's magnetosphere, based on magnetohydrodynamics. It is a 3D Cartesian coordinate model with an inner boundary located at 2.5 Earth radii and solves self-consistently for the location of the magnetopause, bow shock, plasma sheet, and different current systems in the geospace environment.

The Mars Global Magnetosphere Model describes the interaction of the inner heliospheric solar wind with Mars' ionosphere and crustal-remnant magnetic field. A high-resolution spherical grid allows direct modeling of the 3D ionosphere in the magnetosphere module. The model utilizes multiple-species magnetohydrodynamics and allows for the dynamic self-consistent calculation of the boundary between Mars' mini-magnetospheres/ionosphere and the solar wind.

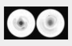
The Mars Upper Atmosphere & Ionosphere Model is a modification of the Earth Upper Atmosphere & Ionosphere Model. The dominant species, ion-neutral chemistry, magnetic field structure, orbit around the Sun, length of day, gravity, and many other things have been changed to allow for the simulation of Mar's thermosphere and ionosphere. This is a 3D spherical code with variable resolution in latitude and altitude and uniform resolution in longitude.



The Saturn Global Magnetosphere Model describes the interaction of the solar wind (inner heliosphere) with the magnetosphere, including important internally driven processes such as Saturn's rapid rotation and the addition of mass due to the planet's rings and moons. The model is based on magnetohydrodynamics and self-consistently determines the location of the boundary between the solar wind and the magnetosphere of Saturn. Adaptive mesh refinement is critically important in modeling Saturn's magnetosphere because of the length-scales for resolving the internal mass loading.

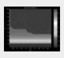


The Saturn Upper Atmosphere & Ionosphere Model is in development. This model will be similar in design to the Earth and Mars upper atmosphere models and will use a 3D spherical grid. The chemistry, species, length of day, etc., will be modified to match the Saturn system.

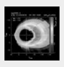


The Saturn Ionospheric Electrodynamics Model is in fact the same model used for Earth simulations. The model easily allows planet-specific parameters, such as conductance, to be set.

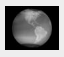
Near-Earth



The Earth Radiation Belt Model simulates the Earth's very high-energy particle population in the inner magnetosphere. These particles are injected into the deep magnetosphere by diffusive and sudden transport processes and then end up trapped there.



The Earth Inner Magnetosphere Drift Physics Model calculates the dynamic behavior of low-, medium-, and high-energy particles in the Earth's inner magnetosphere. As a stand-alone model, it can self-consistently calculate the currents and electric fields in the inner magnetosphere, but as part of the SWMF it drives the particles by applying the electric fields and magnetic field-line topology from different modules.



The Earth Upper Atmosphere & Ionosphere Model simulates the dynamics of the Earth's thermosphere and ionosphere using a 3D spherical grid with variable grid spacing altitude and latitude. It self-consistently models tightly coupled thermosphere and ionosphere systems, solving for how each one influences the other and how the Sun influences both of them.

The Earth Ionospheric Electrodynamics Model calculates the electric potential and the auroral electron precipitation in the Earth's ionosphere. As a stand-alone module, it converts the precipitation pattern and the solar illumination into height-integrated conductances. As part of the SWMF, the precipitation pattern is given to the Upper Atmosphere model, which calculates the conductances self-consistently.

A Sampling of U.S. Space Weather Programs

Center for Integrated Space Weather Modeling
http://www.bu.edu/cism
The goal of this National Science Foundation Science and Technology Center is to create a physics-based numerical simulation model that describes the space environment from the Sun to the Earth. (Sponsor: National Science Foundation)

Center for Space Environment Modeling
http://csem.engin.umich.edu
The overall goal of the center is to develop high-performance, first-principles-based computational models to describe and predict hazardous conditions in the near-Earth space environment extending from the Sun to the ionosphere. (Sponsors: NASA. National Science Foundation, U.S. Air Force, U.S. Department of Defense.)

Community Coordinated Modeling Center
http://ccmc.gsfc.nasa.gov
This multi-agency partnership provides the international research community with access to current-generation space science simulations and supports the transition to space weather operations of modern space research models. (Sponsors: NASA, National Oceanic and Atmospheric Administration, National Science Foundation, U.S. Air Force, U.S. Navy)

Living with a Star
http://lws.gsfc.nasa.gov
The goal of this applications-driven research program is to develop the scientific understanding necessary to effectively address those aspects of the connected Sun-Earth system that directly affect life and society. (Sponsor: NASA)

Solar Multidisciplinary University Research Initiative
http://solarmuri.ssl.berkeley.edu
This collaborative project is studying magnetic eruptions on the Sun and their effects on the Earth's space environment, with an aim of improving our ability to predict space weather from solar observations. (Sponsor: U.S. Department of Defense)

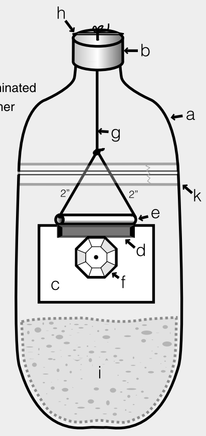
Space Environment Center
http://www.sec.noaa.gov
The center provides real-time monitoring and forecasting of solar and geophysical events, conducts research in solar-terrestrial physics, and develops techniques for forecasting solar and geophysical disturbances. (Sponsors: National Oceanic and Atmospheric Administration, U.S. Air Force)

National Aeronautics and Space Administration
Goddard Space Flight Center
www.nasa.gov

Space Weather Modeling Framework Partners: NASA Goddard Space Flight Center, NASA Jet Propulsion Laboratory, National Center for Atmospheric Research, National Oceanic and Atmospheric Administration Space Environment Center, Rice University, Stanford University, University of Arizona, University of California at San Diego, University of Michigan, and University of New Hampshire

Science Activities

Constructing a Magnetometer



You can build a simple magnetometer to detect changes in the Earth's magnetosphere, the region around the Earth whose processes are dominated by the planet's magnetic field. (Note: This activity is only effective in higher latitudes.) You then work in groups to construct and collect data using a classroom magnetometer. This activity is meant to provide you with a concrete example of technology used by NASA scientists.

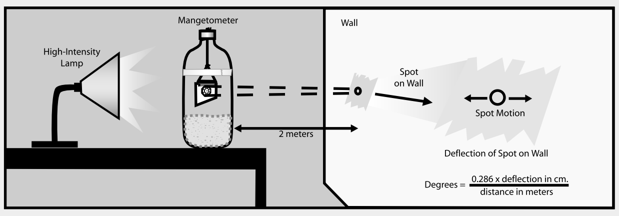
Materials:
(a) 2-liter Soda Bottle
(b) Bottle Cap from Soda Bottle
(c) Index Card
(d) Bar Magnet
(e) Soda Straw
(f) 1/2" Mirror Sequin
(g) Sewing Thread
(h) Toothpick
(i) Sand
(j) Black Permanent Marker
(k) Tape
(l) Glue

Construction Procedure:
1. Clean and dry a 2-liter soda bottle (a). Cut the bottle 1/3 the way from the top. Take the bottle cap (b) and make a small pin hole in the center of the top. Screw it back onto the top of the soda bottle.
2. Cut the index card (c) so that it fits inside the bottle without touching the sides to create a "sensor card."
3. Glue a magnet (d) at the center of the top edge of the card. Cut a 1" piece of soda straw (e) and glue it on top of the magnet.
4. Glue the mirror sequin (f) to the front of the magnet. Mark a dot in the middle of the sequin with a permanent marker (j).
5. Pull thread (g) through the soda straw and tie it into a triangle with 2" sides.
6. Tie a 6" piece of thread (h) to the top of the triangle of thread (g) and thread it through the hole in the bottle cap (b). Secure the thread outside the bottle cap by tying it to the toothpick.
7. Fill the bottom of the soda bottle (a) with 1½" of sand (i) for stability.
8. Tape (k) the bottle back together. Adjust the length of the thread to be sure that the card can swing freely without touching the sides. When you are satisfied with the results, put a dot of glue on the bottle cap to set the toothpick, and thread.

Collecting Data with Your Magnetometer

When used properly, your magnetometer is a good tool for predicting when and where a geomagnetic storm from the solar wind may cause an aurora. The magnetic field from the solar wind interacts with the Earth's magnetic field and causes movement of your magnetometer's sensor card. The interactions of the two magnetic fields will result in the release of a pocket of energy displayed in the sky as the astronomical event over the poles called the aurora. When collecting data, there must be efficient light to make accurate markings on the centimeter scale dark enough so that the reflected light spot can be seen on the scale. All measurements are important and should be taken even if there is no change in the motion of the sensor card.

Materials:
(a) Magnetometer
(b) Strong Bar Magnet
(c) Adjustable High-Intensity Lamp (or Desk Lamp)
(d) Large Sheet of White Paper
(e) Meter Stick (Ruler with Metrics)
(f) Pencil



$$\text{Degrees} = \frac{0.286 \times \text{deflection in cm.}}{\text{distance in meters}}$$

Data Collection Procedure:
1. Place the magnetometer in an undisturbed location of your home where the high-intensity lamp can also be placed. Do not place near another magnetometer, major appliance, or near a window on a busy street. Moving currents and electricity have their own magnetic fields.
2. Place the bottle on a level surface and point the lamp so that a reflected spot shows on a nearby wall about 2 meters away. You should be able to see the reference spot in the middle of a light spot on the scale.
3. On the paper make a centimeter scale with zero (0) in the middle. Make tick marks up to 20 cm on each side. Keep your ruler level.
4. Tape the centimeter scale on the wall directly across from the magnetometer so the mirror spot reflects light onto the scale. (Make sure you can see the light spot during the day and have a light source to make measurements if the area is dark. Be sure the light source is not close to the magnetometer.)
5. Line up the magnetometer 2 meters away from the wall.
6. The first point is the reference point (most preferably zero). Note: If the bottle is moved, then a new reference point must be made.
7. Take measurements every 30 minutes for the duration (at least 2 days so variability in the Earth's magnetic field can be detected). Mark the position of your reference spot within the light spot.
8. You could test that the magnetometer is working by moving a bar magnet or handful of iron nails at various distances from the reference point.
9. The sensor card points at an angle to a horizontal surface – the direction of the magnetic North.
10. When taking measurements, write down the time and movement of the sensor card in centimeters from the scale.
11. Mark the original position of the mirror spot on the scale as your reference point for measuring. Place the bar magnet about 0.5 meters away from the wall near the scale. Mark where the mirror spot has moved on the centimeter scale and note the time as the particular hour of the day.

For more science activities you can perform with your magnetometer, visit:
http://sunearth.gsfc.nasa.gov/sunearthday/2003/fromstudents.htm

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