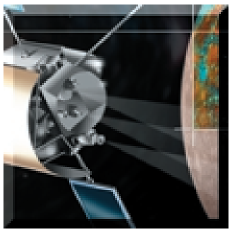


Solar Physics at APL

David M. Rust

Solar research at APL aims to understand the fundamental physics that govern solar activity. The tools are telescopes, models, and interplanetary sampling of solar ejecta. The work is relevant to APL's mission because solar energetic protons disable satellites and endanger astronauts. Solar activity also causes geomagnetic storms, which can lead to communications disruptions, electric power network problems, satellite orbit shifts and, sometimes, satellite failure. Predicting storm conditions requires understanding solar magnetism and its fluctuations. APL scientists have made major contributions to solar activity research and have taken the lead in developing a variety of new solar research tools. They are now starting work on the Solar Terrestrial Relations Observatory, a major space mission. (Keywords: Magnetic storms, Solar flares, Solar magnetism, Solar physics, Solar telescopes.)

INTRODUCTION

At a distance of 150-million kilometers from Earth, the Sun seems far removed from the earthly matters that usually concern APL technologists. Nevertheless, the military and civilian sectors of society have both come to rely heavily on space systems for communications, navigation, surveillance, and natural resource management. As this reliance has grown, the importance of understanding solar disturbances and their effects on space systems has increased concomitantly. Solar events with potential terrestrial consequences can happen at any time; however, their frequency peaks about every 11 years. Near each peak—1969, 1980, 1990—have come well-publicized and not-so-well-publicized satellite system failures. We can expect more problems during the current peak.

One of the earliest recognized hazards to sensitive spacecraft electronics is the proton shower, which is a hail of 50-MeV protons launched in a solar flare. Flares trace their origins to the magnetic strands that are stretched and tangled by the roiling plasma of the unexplored solar interior. In the 1960s and 1970s, APL scientists measured solar protons with Earth-orbiting satellites and tried to predict their strength from solar flare reports, but by the mid-1970s, it had become clear that solar flares had to be understood much better before any meaningful proton shower predictions could be made. NASA's Solar Maximum Mission, known as Solar Max (1980–1989), carried a cluster of telescopes that gave promise of showing where and when protons were released. As a result, Space Department Head George C. Weiffenbach and Chief Scientist Stamatios M. Krimigis decided in 1983 to add solar flare research to the specialties of the Space Physics Group, to try to develop a capability for remotely sensing the solar activity that leads to proton showers and other space disturbances.

In this article, we review how the Laboratory's Space Department built its capability in solar research and how APL scientists contributed to the present understanding of solar flares. The following section reviews contributions to analyses of X-ray images of flares. The next section chronicles how APL efforts have focused on understanding the fundamental physics of solar flares. We have developed theories and telescopes to show how the magnetic fields in sunspots and in the solar atmosphere destabilize and erupt into solar flares and solar mass ejections. Many solar mass ejections contain strong magnetic fields in the form of magnetic clouds. We then discuss APL's role in the development of magnetograph technology. The subsequent section explores how magnetic clouds are ejected from the Sun and how they affect Earth. APL scientists helped show how telescopic measurements of solar eruptions can forecast the direction of the magnetic fields in the ejected clouds. Finally, we look to the future, to the Solar Terrestrial Relations Observatory (STEREO) in particular, with its cluster of telescopes and plasma sensors. STEREO will be launched in 2003 or 2004. Although it is a research mission, it will strengthen real-time space weather forecasts, and it may arrive in time to reduce the risk that astronauts constructing the International Space Station will encounter a proton shower.

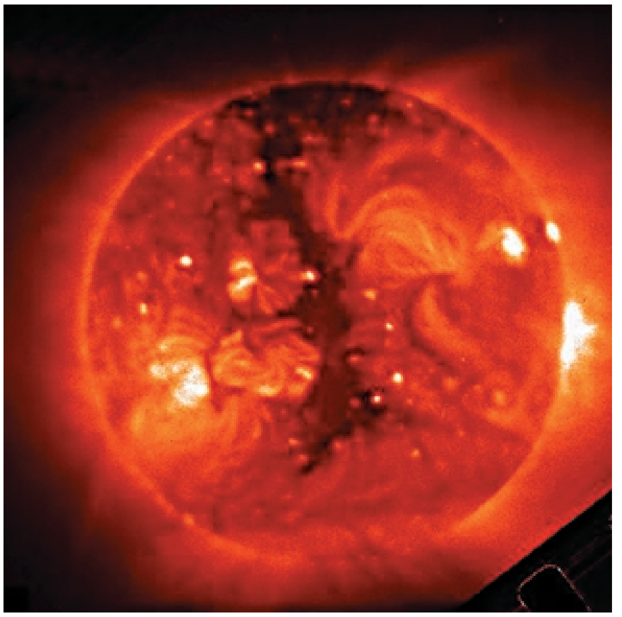


Figure 1. The solar corona as seen from Skylab on 31 May 1974. The bright areas show where X rays are emitted from 1-million-degree ionized plasmas trapped in magnetic fields.

SOLAR FLARES AND X-RAY TELESCOPES

The origins of proton showers must be sought in the upper reaches of the solar atmosphere called the corona. Strongly accelerated protons could never escape the Sun if they had to penetrate the lower, denser atmosphere, or chromosphere. The Skylab mission (1973–1974) carried two telescopes that could focus the X-ray emission from the corona (Fig. 1), which has a temperature of over 1 million degrees. APL scientists studied the Skylab X-ray images, which showed the hot magnetic arches in the corona above sunspots, but found that they provided little detail about the hottest cores of flares. These 100-million-degree features, we thought, could be the sites of proton acceleration.

Images obtained with the Hard X-ray Imaging Spectrometer (HXIS) aboard the Solar Max[1] provided a better opportunity for finding the acceleration sites. HXIS photographed the 100-million-degree flare plasmas every 1.5 s. It showed that flares are like two uninsulated high-voltage electric cables that have been brought too close together. Where they collide, the plasma is heated rapidly. However, instead of expanding in a shock, as one might expect of such a rapidly heated gas, the high-temperature flare kernels hardly moved at all. This presented a problem if flares were to be the source of proton showers. The only way we and most others could imagine accelerating protons was to trap them between a shock front and the ambient atmosphere. We had to conclude from the HXIS images that the magnetic fields in X-ray flares were too strong to allow the gases to break out and form shocks.

The Solar Max telescopes helped us to build a three-dimensional model of a flare, but they did not help much in understanding proton showers. Here, it is important to recognize that although our goal is to understand and forecast space weather, the path there is not straight and cannot be forced. When new instruments or insights open interesting new lines of inquiry, we, like scientists at other universities and major research institutions, are encouraged to pursue them. Thus, we studied the images from the Solar Max telescopes and showed that an X-ray-emitting front does sometimes develop in flare loops. Strong magnetic fields constrain the fronts, which can only rush from the flare site to the points where the magnetic loops intersect the solar surface. The fronts propagate at about 1000 km/s, and they carry away most of the thermal energy developed in the flares. We concluded that the fronts are evidence for electron thermal conduction. If this interpretation is correct, then the conduction fronts seen in the HXIS images would be the first to have been detected in an astrophysical context.

Solar Max did not carry the sort of full Sun-viewing X-ray telescope that Skylab did, and in the mid-1980s it was recognized that if proton-producing flares were to be understood, then a Skylab-type telescope was needed. APL scientists worked with their counterparts from other institutions to develop a flare research mission that would combine the Skylab-type soft X-ray imager, which sees the 1-million-degree ambient solar atmosphere, with a Solar Max–type hard X-ray imager, which sees the 100-million-degree flares. We took our ideas to the Japanese Space Agency because NASA could not afford a solar research satellite in the budget-lean years of the 1980s. From these discussions came the immensely successful Yohkoh spacecraft, which was launched in 1991 and continues with successful observations today.

The Yohkoh images seen in Fig. 2 are much sharper and more plentiful than those obtained with the Skylab telescopes. The Yohkoh has acquired millions of images compared to only a few thousand from Skylab. Its impact on flare research has been impressive,[2] and APL scientists have contributed to the scientific accomplishments of the Yohkoh Soft X-ray Telescope. One of the most exciting discoveries was that a type of magnetic instability well known in laboratory research apparently takes place during the onset phase in solar flares. This helical kink instability is similar to the instability or sudden formation of knots that occurs in a rubber band when it is twisted too much.[3]

Most flare events in the Soft X-ray Telescope images evolved from a bright, sharp-edge sigmoid (S-shaped) feature into either an arcade of flare loops or a diffuse cloud. A spectacular example of evolution into a classic loop arcade is shown in Fig. 3. We studied 103 such transient, bright sigmoid structures and compared the proportions of 49 of the best-defined ones with the signature of a helical kink instability. The sigmoid structures had an average width of 48,000 km and an average length of 200,000 km. For comparison with the kink instability, we prepared a histogram of the length-to-width ratio. The histogram has a peak near 5.0 with a

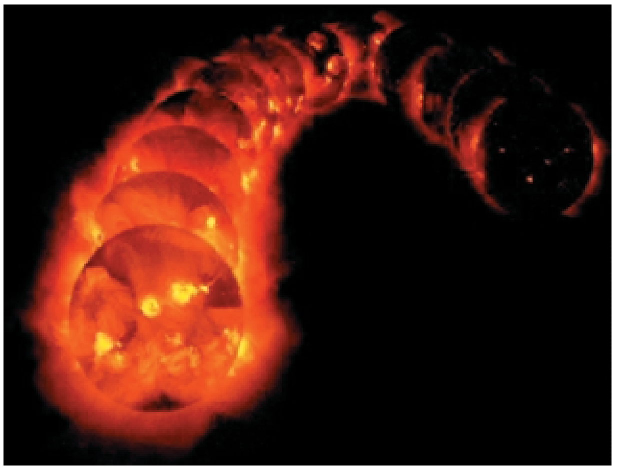


Figure 2. Representative X-ray images of the Sun, at approximately 6-month intervals since 1991 (time runs left to right). The corona is much brighter and filled with detail near the peak of solar activity in 1991. (Figure courtesy of Lockheed, National Astronomical Observatory of Japan, University of Tokyo, NASA, and ISA.)

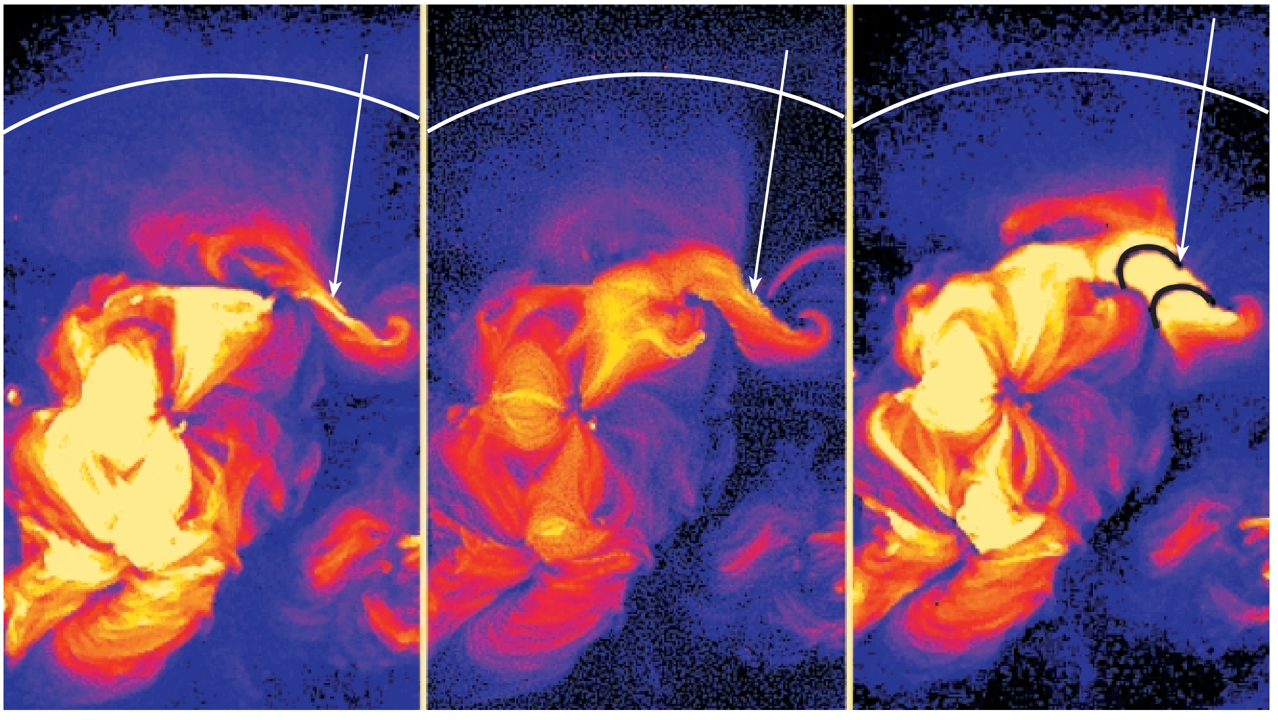


Figure 3. Development of a flare in the solar X-ray corona. The arrow in the leftmost image points out the reverse-S feature that signals the onset. In the middle image, which was made with a shorter exposure time, the arrow shows the beginnings of the transformation into a flare loop arcade. In the final image (right), the arcade is fully developed and very bright. Two black curves were drawn on the image to help show the shape of the loops. The white arcs in each panel outline the solar limb.

slow drop-off toward higher values and a rapid drop-off toward lower ones. This distribution is consistent with what would be expected if most sigmoid features arch upward or downward more or less in the line of sight.

We concluded that the length-to-width ratios and the shapes of the bright features are consistent with helically kinked magnetic flux ropes. A magnetic flux rope is a nearly self-contained magnetic field whose lines of force somewhat resemble the strands in a rope. Whereas stability depends on many conditions, those with more than a 360° twist are usually unstable. Although there are no generally accepted models of how the instability grows into an eruption, it is likely that the twisted magnetic fields inside the flux rope reconnect and release heat as the rope kinks and stretches.

Previous research had determined flare temperature, density, heating and cooling rate, etc., but never before was a distinctive and quantifiable signature of a specific instability discovered. Now finally, from this analysis of X-ray images, we have a physical explanation and hard evidence for the kind of solar eruption that might become a shock in the corona and that might, therefore, have something to do with proton showers. Parallel work at the Laboratory and other institutions was also building a case for focusing on the twisted magnetic flux ropes.

APL scientists usually send such research results to *The Astrophysical Journal* or the *Journal of Geophysical Research*. That route gets the word out in the long run; however, to speed up the exchange of research results, we organize meetings and lecture at other institutions. For example, when the importance of the twisted flux tubes became evident, we organized a special session at a meeting of the American Geophysical Union to explore such helicity in various contexts, in the laboratory and in space.

THE CENTRAL ROLE OF SOLAR MAGNETIC FIELDS

While images can help us understand quite a lot about the magnetic fields confining flares, we are unlikely to be able to predict when a flare will occur without actually knowing the magnetic field strength. APL scientists had been measuring magnetospheric magnetic fields since the Transit Program (see the article by Williams et al., this issue), but until 1984 there was no program to remotely sense magnetic fields on the surface of the Sun. By the mid-1980s it was widely recognized that a solar magnetograph program had to be established, even though it would involve a very difficult instrumentation development effort. New instruments, probably using new technology, would be needed. Consequently, we mounted a small, amateur telescope on the roof of Building 2 to test new instrument ideas. We began development of a high-speed imaging system by connecting a video camera attached to the telescope to the McClure Computing Center in Building 3. Those were the days when image processing was done at considerable expense at central computer facilities. However, the McClure management was interested enough in the project to grant us some free use of their facilities.

On the basis of what we accomplished, the Air Force Office of Scientific Research selected APL to establish the Center for Applied Solar Research. The first task was to build a solar vector magnetograph, which is a specialized telescope for three-dimensional mapping of the fields in the Sun's surface. Specifically, our goal was to measure all three components of the magnetic field with a sensitivity of 0.005 T and a spatial resolution on the Sun of 500 km. Such specifications were beyond the reach of existing instruments; nonetheless, we hoped that by using new optical devices, such as ultra-narrow passband optical filters, liquid-crystal polarization modulators, and a solid-state camera based on charge-coupled device technology, we could break through the barriers that confronted the older generation of instruments.

So far, we have only partially succeeded. We built a vector magnetograph (Fig. 4) and installed it on a

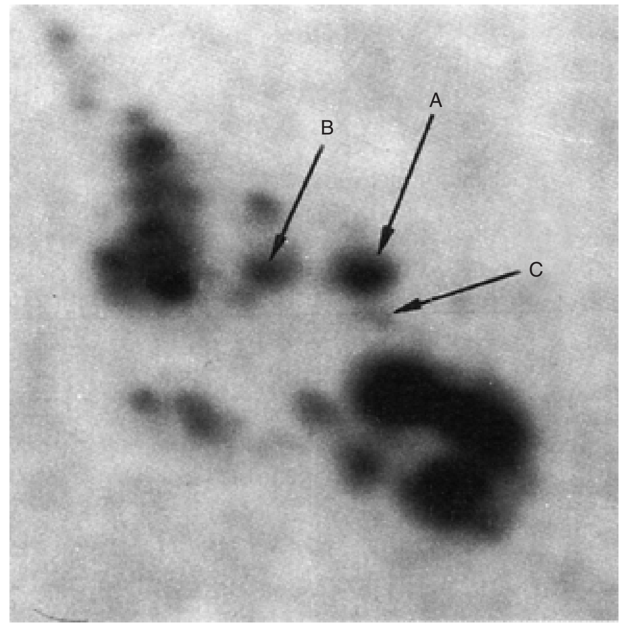
Figure 4. The APL solar vector magnetograph installed at the National Solar Observatory in Sunspot, New Mexico.

mountain ridge at the Sacramento Peak Observatory overlooking Alamogordo, New Mexico.[4] It was hoped that there, at an elevation of 9300 ft, the “seeing” (image jitter due to turbulence in the Earth’s atmosphere) would be much less than at lower-elevation observatories. This turned out not to be the case, so the full resolving power of the telescope was not realized.

Many measurements of the magnetic fields in flare-prone groups of sunspots were made, though, and in one case we obtained observations before and after a major flare. Observations of a flare on 2 April 1991 appeared to confirm earlier evidence that eruptive flares were triggered by measurable magnetic field changes. In the 8 hours before the flare, the electric currents flowing parallel to the magnetic fields increased in intensity. The development that likely triggered the flare was the emergence of new magnetic flux (Fig. 5) into the sunspot region. Data from our vector magnetograph also showed that the motion of the newly emerged spots led to the development of stronger electric currents. The flare started near the newly energized fields and spread to engulf most of the sunspot region. A magnetogram taken 45 min after flare onset showed possible relaxation of the sheared fields.

The APL observations appeared to confirm a model[5] of solar flare magnetic fields put forward in 1977 by Jean Heyvaerts of the Paris Observatory, Eric Priest of St. Andrews University in Scotland, and the author, then at American Science and Engineering, Inc., in Cambridge, Massachusetts. The idea is that sheared or twisted magnetic fields in the atmosphere above sunspots become unstable and erupt when new magnetic flux (usually also detectable as sunspots) emerges. With observations tending to confirm this 20-year-old two-dimensional model and with much better insight now into the physics of flux ropes, current flare research is focused on making more realistic, three-dimensional models of the effects of emerging flux.

The work on flares illustrates how observations and theory are intertwined. Although the emphasis at APL is on observations and measurement of the space environment, the context provided by theory allows us to integrate our experiences and finally understand how physical forces and energies operate in space.



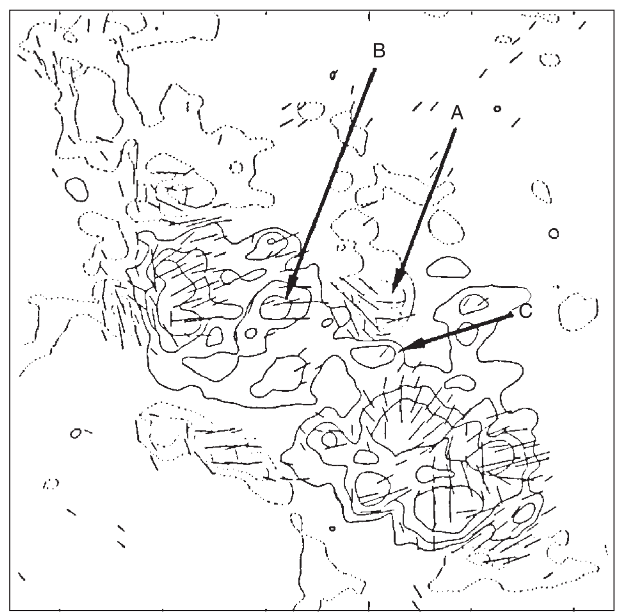


Figure 5. Photograph (top) and maps of the magnetic fields (bottom) of two spots, A and B, that emerged into the group of larger spots and triggered a major solar flare. The magnetic gradient between spots A and C steepened as spot A emerged and grew. Similar increases have been noted by others in other sunspot groups and have been identified with increased flare productivity.

IMPROVEMENTS IN MAGNETOGRAPHS

The primary objective for APL’s first magnetograph was to test new components, particularly those that could lead to a lightweight magnetograph in space. Most magnetographs, which require a wavelength selection device, had been built around either a spectrograph or a birefringent filter. Solar spectrographs for research at visible wavelengths are simply too large for practical space missions. Birefringent filters are proven instruments, but they are relatively heavy. They have been flown only on the Space Shuttle and on the Solar and Heliospheric Observatory (SOHO), which is a much larger spacecraft than can be considered seriously for today’s solar missions such as STEREO.

APL and the Australian National Measurement Laboratory developed a lightweight optical filter[6] capable of isolating the wavelengths in the solar spectrum that are used in measuring the magnetic fields on the visible surface. The filter, a Fabry-Perot etalon made of lithium niobate, is rugged and much lighter than any birefringent filter. However, the technology was quite new in 1987 when APL proposed it for the SOHO mission; consequently, NASA selected a magnetograph based on the established technology of birefringent filters.

Lithium-niobate etalons are now in use in several observatories around the world. APL scientists used one in the magnetograph in New Mexico and in the Stable Solar Analyzer, which measured solar oscillations.[7] We also worked with the Space Department's Frequency Standards Group to demonstrate that the filter could be combined with a tunable laser and an atomic reference cell to provide ultrastable solar wavelength measurements.[6] Here is an example of the synergy that often develops in the Space Department, where many diverse high-technology skills are available.

APL scientists have continued to develop magnetographs for use in space. Having concluded that space is the only reasonable venue for a magnetograph, we worked with other interested scientists to develop the Orbiting Solar Laboratory (OSL) for NASA. The centerpiece of the OSL would be a large vector magnetograph. We served on numerous committees formed to refine and promote this mission.

When another NASA budget crisis doomed the OSL in 1991, we started work on the Flare Genesis Experiment (FGE), a balloon-borne solar telescope.[8] The FGE would incorporate all the advanced technology we had developed for a space mission and demonstrate it in the near-space conditions provided by a balloon flight at a 37-km altitude.

On the face of it, the FGE seems a retreat to old technology, because a balloon instead of a rocket carries it above the atmosphere. But ballooning in Antarctica is new. It even offers special advantages over most satellites, because the Sun can be studied without interruption during the Austral summer for periods of usually about 14 days. Twenty-eight-day flights are possible. The first FGE flight lasted 18 days. Another flight is planned for December 1999.

The principal science goal of FGE is to understand how the fibrous magnetic fields at the solar surface emerge, coalesce, unravel, and erupt in solar flares. The principal technology goal is to demonstrate that new APL systems for image stabilization, wavelength isolation, polarization analysis, and onboard control can provide reliable observations in a space environment. These systems must maintain the desired resolution of ≈0.2 arcsec (corresponding to only 140 km on the solar surface) despite pendulation and wind buffeting of the balloon and its payload.

The FGE benefited from the end of the Cold War. Just as NASA was deciding that it could not afford the OSL, the Strategic Defense Initiative Organization (SDIO) encountered technical difficulties with Starlab, a project to illuminate enemy satellites with laser light from a large telescope in the Space Shuttle bay. SDIO asked APL Space Department scientists how best to use the valuable Starlab telescope. We showed that with minor modifications it would be ideal for solar research and, as a result, it was transferred to the FGE Project.

The primary mirror of the Starlab telescope is 80 cm in diameter, making it one of the world's largest mirrors for solar research. Figure 6 shows the telescope in the balloon gondola in Antarctica. The Starlab telescope body is made of graphite-epoxy fiber, and the mirrors are ultra-low-expansion glass. A large solar telescope for space would probably use the same approach to minimize dimensional changes as the telescope orbits into and out of the sunlight. The other key high-technology elements of the FGE are the single-crystal silicon secondary mirror, liquid-crystal polarization modulators, the tunable lithium-niobate optical filter, an image motion compensator, and a fast electronic camera.

The first FGE flight lasted from 7 to 26 January 1996—one of the longest balloon flights yet in Antarctica. The telescope remained locked on the Sun for the entire flight. The data collection system obtained over 14,000 images. Although a number of problems limited

Figure 6. The Flare Genesis Experiment ready for launch in Antarctica, 7 January 1996. The solar telescope is wrapped in a white thermal control blanket. The solar panels supply 1300 W of power, most of which is needed to drive the pointing motors.

the resolution on the first flight to ≈1 arcsec, the major FGE systems performed as expected.

The problems on the first flight have been studied and corrected. High resolution, great stability during solar observations, and long runs without interruptions cannot be achieved with any other existing instrument. With these advantages, we expect the next flight of the FGE, scheduled for December 1999, to reveal key features of the mechanisms of magnetic energy buildup and release in solar flares. The FGE is uniquely capable of observing these processes, and solar activity should be at its peak during the flight.

A NEW TWIST ON SOLAR MAGNETISM

Solar research at APL took an unforeseen twist in 1993 when Sara Martin at the California Institute of Technology and Norbert Seehafer at the University of Potsdam, Germany, found a global organization in the solar surface magnetic fields. Magnetic flux ropes can be twisted in either the right-handed or left-handed sense, depending on whether their electric currents flow parallel or antiparallel to the magnetic field. What Martin and Seehafer found was a tendency for flux ropes in the Sun's northern hemisphere to have left-handed twists. Those in the Sun's southern hemisphere tended to have right-handed twists. What if the magnetic fields in the ejected clouds of material also reflect this pattern? It might be a key to understanding how the kink instability works on the Sun. Using data from many satellites, we were able to show that when a left-handed magnetic flux rope was ejected toward Earth, then the cloud's field, as measured by near-Earth spacecraft such as the Advanced Composition Explorer (ACE) and others, would also be left-handed.

The magnetic cloud phenomenon is an interesting and practical demonstration of the principle of magnetic helicity conservation.[9] If left-handed fields emerge in the north and form sunspots, then shouldn't the flux ropes that spring from them be left-handed? Shouldn't the coronal magnetic arcades be left-handed? Finally, shouldn't the fields ejected from the northern hemisphere be left-handed? We found that more than 80% of magnetic clouds have the chirality (handedness) predicted by the hemispherical segregation rule. The picture that emerged is one of helicity buildup in the solar atmosphere by flux rope mergers and helicity transfer from the submerged flux rope parts.[10] When the magnetic helicity becomes too large for the confines of the corona, we get a helical kink instability and consequent flux rope eruption. Measurements with ACE, the Near Earth Asteroid Rendezvous (NEAR), and other spacecraft verify that the helicity in the flux rope is the same as when it leaves the Sun.

The seemingly academic work on helical magnetic fields will have a significant effect on space weather forecasting. Geomagnetic storms are major space weather disturbances. In these storms the Earth's magnetosphere and ionosphere change suddenly and strong currents surge through the ground, the upper atmosphere heats up, and charged particles accelerate in the Van Allen belts. These phenomena lead, in turn, to communications disruptions, electric power network problems, satellite orbit shifts, and possibly satellite failure.

The intensity of geomagnetic storms depends, among other things, on the direction of the fields in the clouds that leave the Sun. We can improve forecasts of individual storms because the NASA/ESA (European Space Agency) SOHO mission and other facilities allow us to see the erupting features better and to correctly infer their magnetic field structure on the Sun. We can predict their pattern of impact at Earth by applying helicity conservation. Moreover, because of the global patterns of magnetic fields on the Sun, we can predict that geomagnetic storms during the present solar cycle, 1995–2006, will be more intense than in the previous cycle. Thus we can make a prediction about the climate in space for this decade.

Why are the helical fields segregated north and south? Could the observed pattern change with time? Recent magnetographic research has found that quantitative changes do occur during the solar cycle. However, a review of old pictures and research has shown that in each of the past seven solar cycles (about 77 years) the magnetic fields remained predominantly right-handed in the south and left-handed in the north. The classical Coriolis force produces a similar unchanging hemispherical segregation in terrestrial cyclones, but the helicity on the Sun does not follow the patterns that we would expect from the Coriolis force. Instead, the helicity pattern is consistent with a model (Fig. 7) in which the internal field is wound up by rotating plasmas inside the Sun. The differential solar rotation will produce left-handed twist in the northern fields and right-handed twist in the southern ones for all solar cycles, of course, because the direction of the Sun's rotation never changes.

The model in Fig. 7 is not much better than an inspired sketch, but more sophisticated solar dynamo models also produce opposite magnetic helicities north and south of the equator. Even these computer models leave many important features out, so we really have no consistent theory of how solar magnetic fields are generated and how they destabilize every 11 years. To make the next major improvement in understanding the Sun and space weather, we need a global view of solar magnetism. With the STEREO mission, described in the next section, we are setting out to get that global view.

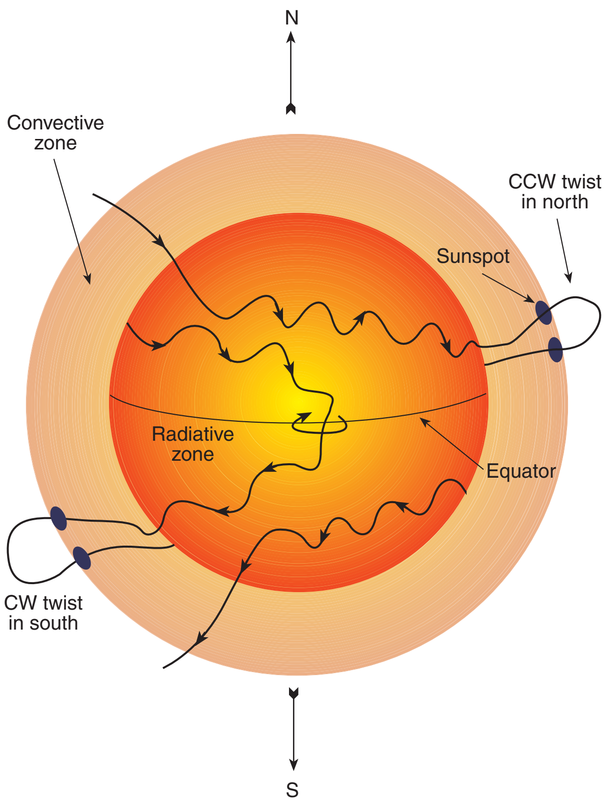


Figure 7. Cross section of the Sun showing one concept of how magnetic lines of force at the boundary between the interior (radiative zone) and the convective zone twist and rise to the surface, where they appear as sunspots. Near the equator, magnetic fields running from north to south will become twisted because the gases in the convective zone rotate faster than those in the radiative zone. The effect would produce clockwise (CW) twist in the fields in the south and counterclockwise (CCW) twist in the north, as is actually observed. Alternatively, Coriolis forces may twist the fields. The twisted fields will accumulate in the solar atmosphere above the convective zone and then erupt and leave the Sun as coronal mass ejections (Fig. 8).

THE FUTURE OF SOLAR RESEARCH AT APL

It took a decade from the Space Department's decision to add solar research with telescopes to APL's established strengths in solar particle detection, but it paid off. Only close familiarity with both types of measurements could have produced our improved understanding of solar magnetism and its application in forecasting space weather.

Although it is impossible to foresee what new ideas will emerge, we expect that solar activity and its effects will be a central factor in our work. Last year, APL scientists played a major role in formulating NASA's Sun–Earth Connections Program. Its aims are to improve mankind's understanding of the origins of solar variability: how that variability transforms the interplanetary medium, how eruptive events on the Sun impact geospace, and how they might affect climate and weather.

NASA has just asked us to study how magnetic flux ropes evolve from their departure at the Sun to their arrival at Earth orbit. The principal data sources are to be solar images (Fig. 8) from the SOHO telescopes and magnetometer data (Fig. 9) from APL's NEAR mission. The SOHO/NEAR constellation has some of the features of the future STEREO mission (Fig. 10). SOHO solar telescopes most clearly show eruptions leaving at a 90° angle to the Earth–Sun line. During much of its flight, the NEAR spacecraft will be in an ideal position to sample the plasma in these eruptions. Figures 8 and 9 provide one example of how telescopic observations of cloud structure can be used with *in situ* measurements to build a more complete picture of magnetic flux rope structure and its evolution from ejection at the Sun to passage near Earth.

APL scientists played a major role in defining the science goals and instrument payload of the STEREO mission, and NASA selected APL to provide the STEREO spacecraft bus and to manage mission operations. STEREO will consist of two spacecraft, one leading Earth in its orbit and the other lagging. Each will carry a cluster of telescopes to study solar activity, and each will carry a magnetometer, a solar wind detector, and energetic particle detectors to sample solar ejections. Thus, magnetic clouds and other disturbances can be tracked from their departure at the Sun to their arrival at various points at Earth's orbit.

STEREO will be launched in 2003 or 2004. It is one of five Solar-Terrestrial Probes called for in NASA's

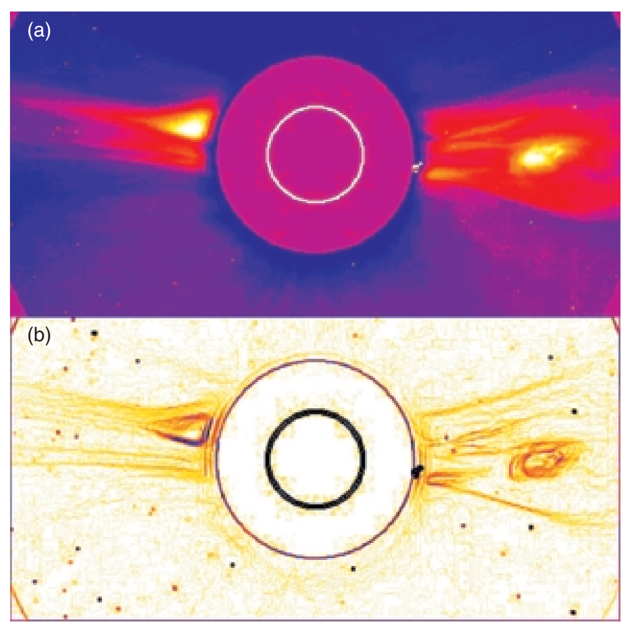


Figure 8. (a) The Sun ejected this bright cloud (right) known as a coronal mass ejection on 13 August 1997 in the direction of the NEAR spacecraft. (b) Edge-enhanced version, which gives a faint indication of a circular feature in this cloud. Many other similar clouds exhibit clear circular arcs that could be signatures of a twisted magnetic flux rope seen end-on.[11]

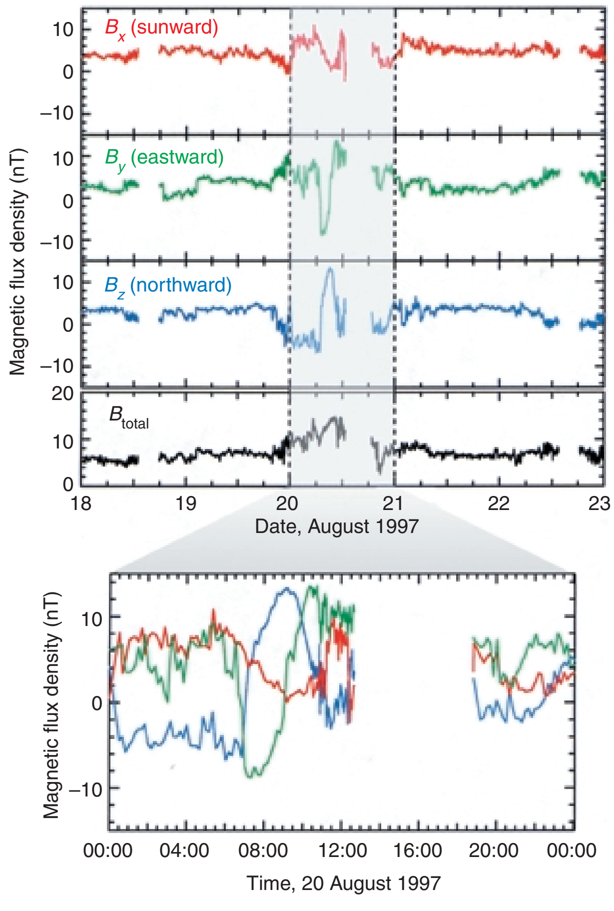


Figure 9. NEAR magnetometer record of magnetic field components, B_x, B_y, and B_z, for the period 18–23 August 1997. The disturbance on 20 August followed the ejection of the cloud shown in Fig. 8 by the expected "time of flight" that we calculated from the cloud velocity and the distance of the NEAR spacecraft from the Sun. The expanded view (bottom) of the magnetic field measurements shows that the eastward component B_y (green) of the field rotated as one would expect in sampling a twisted magnetic flux rope.

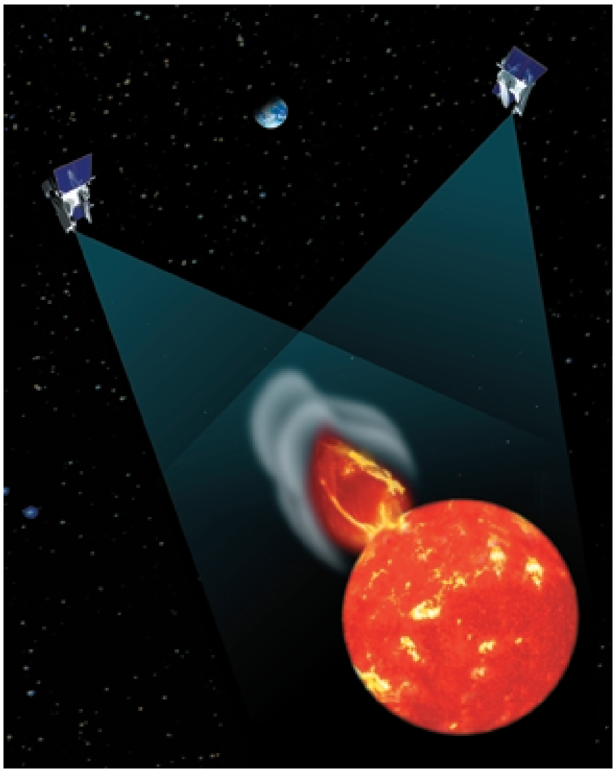


Figure 10. An artist's concept of the two STEREO spacecraft viewing a solar eruption.

Space Science Enterprise Strategic Plan to accomplish the goals of the Sun–Earth Connections Program. The other missions and their likely launch dates are as follows:

- TIMED, the Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics mission (2000)
- Solar-B, which will obtain high-resolution images of the solar magnetic field (2005)
- Magnetospheric Multiscale, which will provide a network of *in situ* measurements of Earth's magnetosphere (2006)
- Global Electrodynamics, which will probe Earth's upper atmosphere to determine how variations in particle flux and solar electromagnetic radiation affect it (2008)

Although STEREO will probably dominate our solar research efforts in the near future, we are working on other ideas as well: solar neutrinos as probes of the internal magnetic fields (some evidence[12] show that neutrinos have a magnetic moment and that the twisted magnetic fields modulate their passage through the Sun's interior); Solar Probe, a spacecraft that will fly to within 4 solar radii of the Sun and sample the corona and solar wind; a DoD constellation of satellites to improve space weather forecasts; and telescopes two or three times bigger than Flare Genesis to give the highest possible resolution to solar images. These large telescopes will probably be flown first on balloons and then possibly on the International Space Station.

Eventually, we hope to develop a mission patterned on STEREO to provide data for routine forecasts on weather throughout the heliosphere. Such a mission will be needed, particularly some time after 2020 when man will likely undertake interplanetary travel.

Solar research at APL has been a quest to understand the origins of energetic solar protons, the causes of geomagnetic storms, and the fundamental physics that govern solar activity. We will likely continue in this vein with larger telescopes, more sensitive magnetographs, and more detailed computer models. Despite our efforts and those of hundreds of solar physicists around the world, we still cannot agree on even some of the most fundamental issues. We will keep trying to solve them and benefit the nation's space enterprise as well.

REFERENCES

[1]Rust, D. M., "The Solar Maximum Observatory," *Johns Hopkins APL Tech. Dig.* **5**(2), 188–196 (1984).

[2]Bentley, R. D., and Mariska, J. T. (eds.), "Magnetic Reconnection in the Solar Atmosphere, Proceedings of a Yohkoh Conference," *Astron. Soc. Pacific Conf. Ser.* **111** (1996).

[3]Rust, D. M., and Kumar, A., "Evidence for Helically Kinked Magnetic Flux Ropes in Solar Eruptions," *Astrophys. J. Lett.* **464**, L199–L202 (1996).

[4]Rust, D. M., O'Byrne, J. W., and Harris, T. J., "An Optical Instrument for Measuring Solar Magnetism," *Johns Hopkins APL Tech. Dig.* **9**(4), 349–359 (1988).

[5]Heyvaerts, J., Priest, E. R., and Rust, D. M., "An Emerging Flux Model for the Solar Flare Phenomenon," *Astrophys. J.* **216**, 123–237 (1977).

[6]Rust, D. M., Kunski, R., and Cohn, R. F., "Development of Ultrastable Filters and Lasers for Solar Seismology," *Johns Hopkins APL Tech. Dig.* **7**(2), 209–216 (1986).

[7]Appourchaux, T., and Rust, D. M., "The Stable Solar Analyzer," in *Proc. Symp. on Seismology of the Sun and Sun-like Stars*, European Space Agency, **SP-286**, 227–234 (1988).

[8]Rust, D. M., Hayes, J. R., Lohr, D. A., Murphy, G. A., and Strohbehn, K., "The Flare Genesis Experiment: Studying the Sun from the Stratosphere," *Johns Hopkins APL Tech. Dig.* **14**(4) 358–369 (1993).

[9]Glanz, J., "Does Magnetic Twist Crank Up the Sun's Outbursts?" *Science* **269**, 1517 (Sep 1995).

[10]Bieber, J. W., and Rust, D. M., "The Escape of Magnetic Flux from the Sun," *Astrophys. J.* **453**, 911–918 (1995).

[11]Dere, K. P., Brueckner, G. E., Howard, R. A., Michels, D. J., and Delaboudiniere, J. P., "LASCO and EIT Observations of Helical Structure in Coronal Mass Ejections," *Astrophys. J.* **516**, 465–474 (1999).

[12]Rust, D. M., and McNutt, R. L., Jr., "Neutrinos and Helical Magnetic Fields on the Sun—Results of Observations," in *Proc. Fourth Int. Solar Neutrino Conf.*, W. Hampel (ed.), Max Planck Inst., Heidelberg, Germany, pp. 380–387 (1997).

ACKNOWLEDGMENTS: The Solar Physics Program at APL has been supported by NASA's Solar Physics Program Office, the NSF Polar Aeronomy and Astrophysics and Solar Terrestrial Physics Programs, and the Air Force Office of Scientific Research. Additional support was provided by the APL graduate and postdoctoral fellowship programs and the IR&D programs. At APL, John O'Byrne, Graham Murphy, Pietro Bernasconi, Ashok Kumar, and Brian Anderson have contributed to the program. In addition, I am grateful for the dedicated support on many projects of the engineering staffs of the Space Department and the Technical Services Department.

THE AUTHOR

DAVID M. RUST received his Sc.B. degree in physics from Brown University and his Ph.D. in astro-geophysics from the University of Colorado. He joined APL in 1983. A member of the Principal Professional Staff since 1985 and Solar Physics Section Supervisor, Dr. Rust has initiated programs to analyze solar X-ray emissions; build new solar telescopes, optical filters, and detectors; and map solar surface magnetic fields. He also established the APL Solar Observatory. He has published over 100 refereed papers on solar physics. He has also published papers on instruments for solar research. Dr. Rust was granted patents for a vector magnetograph and an imaging polarimeter. His current interests include development of a balloon-borne solar telescope and design of the STEREO mission. His e-mail address is david.rust@jhuapl.edu.