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THE FLARE GENESIS EXPERIMENT: STUDYING THE SUN FROM THE STRATOSPHERE

The APL Space Physics Group is preparing to fly one of the largest solar telescopes in the world. For two weeks in 1994, the balloon-borne Flare Genesis Experiment will float in sunlight well above the turbulent, image-blurring layers of the Earth's atmosphere, supplying images to a vector magnetograph that will map solar magnetic fields. The images will capture magnetic features 10 times smaller (100 miles vs 1000 miles across) than any detectable from the ground. In subsequent annual Antarctic balloon flights, the Flare Genesis Experiment will provide additional unprecedented details about sunspots, flares, and the solar atmosphere. The program will advance basic scientific understanding of the mechanisms of solar variability and provide practical engineering experience for the design and operation of a Sun-monitoring observatory in space. Forecasts from such an observatory will make space missions safer and more dependable.

INTRODUCTION

Man has been fascinated with the Sun and the stars since he first walked on the Earth. The Druids and other prehistoric societies constructed observatories, like Stonehenge, to help them understand the annual and daily cycles of astronomical bodies. Throughout history and prehistory, man has been so interested in the heavens that, after weapons, astronomical instruments have arguably been the chief focus of his labors in advanced technology.

The marriage of high technology and astronomy continues today as we try to peer ever closer to the edge of the universe with large and complex telescopes. In solar astronomy, we continue, in the tradition of Galileo, to look for the finest details on the surface of the Sun and to understand how changes in the Sun influence life on Earth.

We are entering an era of predictive solar science. We can predict when the global magnetic field will next reverse and, sometimes, how and when a storm from the Sun will strike the Earth. But no one fully understands the sunspot cycle, and solar physicists can still tell us relatively little about the inner mechanisms of solar eruptions. These are not just academic problems—shock waves and atomic radiation from solar flares can bring down satellites before their time or cripple their computers. Thus, solar physics is an essential element of space environment research in APL's Space Department.

To better understand solar activity, we have initiated a program, called the Flare Genesis Experiment (FGE), to obtain the sharpest pictures ever of the Sun and its atmosphere. The FGE will use one of the largest and most advanced solar telescopes in the world to measure the magnetic fields and motions on the solar surface. Some

very modern technology is available to us, including optical devices that we invented for our program and some that were developed in the Cold War. In fact, the end of the Cold War is giving us access to high-technology equipment that would otherwise be beyond the means of solar research programs. It is reminiscent of the fruitful period following World War II, when, for example, scientists at APL and other institutions inherited the V-2 rockets.

BALLOONING IN THE ANTARCTIC

On the face of it, the FGE seems a retreat to old technology because a balloon instead of a rocket will carry it above the atmosphere. But war-surplus rockets and satellites as platforms for space experiments are still hard to come by. Moreover, ballooning *in Antarctica* is new. It even offers astronomers special advantages over most satellites, because the Sun, the planets, and many stars can be studied without interruption during the Austral summer, usually for periods of about 14 days but with 28-day flights possible.

Long-duration ballooning in Antarctica began in 1988 when Prof. Carl A. Rester of the University of Florida flew a gamma-ray telescope that had been grounded by the suspension of Space Shuttle flights. His target was Supernova 1987A, which exploded in the Southern sky in February 1987 and was the closest such event to Earth since the famous one in 1604 recorded by Kepler and others. Shortly after Supernova 1987A appeared, Rester realized that he might be able to detect the gamma rays from the element-building processes in it with his telescope, but to do so, he would have to boost his detector

above most of the atmosphere and keep it there for a week or more.

Since the supernova was in the Southern Hemisphere, a stratospheric balloon flight in Antarctica would provide the perfect viewing platform. Vortical winds would carry it on a slow circumnavigation of the South Pole (see Fig. 1). But no one had ever done it before. Worse, the kind of helium-filled balloon he needed had not been a very reliable vehicle in the 1980s. Many payloads had fallen straight to the ground after the balloon film stiffened and cracked in the -50°F cold of the stratosphere.

With support from the Air Force Geophysics Laboratory and many other agencies, Rester decided to launch a balloon in the 1987–1988 Austral summer. The National Science Foundation (NSF) was enthusiastic about the project and joined the consortium of sponsoring agencies. The NSF's Division of Polar Programs supports U.S. research in Antarctica from its base at McMurdo Sound. Because Earth's magnetic fields open into outer space near the poles, thereby providing freer access to the atmosphere for cosmic rays and solar particles, Antarctica has been known as a "window on space" since the International Geophysical Year in 1959.

Rester's mission was a phenomenal success.¹ He not only detected the gamma rays and verified the theory about how supernovas make the elements, but he and his consortium opened Antarctica to long-duration scientific ballooning. Since then, balloons have flown successfully many times, thanks to NASA's National Scientific Ballooning Facility and the development of highly reliable balloon film.

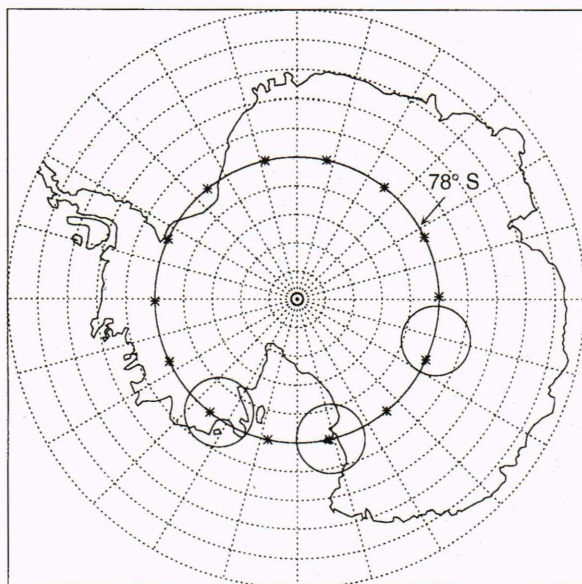


Figure 1. The projected flight path of the Flare Genesis Experiment in Antarctica, starting from McMurdo base, passing over Russia's Vostok station and Byrd station, over the Ross Ice Shelf and finally back to near McMurdo. Actual flight paths in previous balloon experiments have deviated by hundreds of miles from the ideal 78° South latitude circle shown here. The small circles show the maximum range of radio contact with the package.

SOLAR VECTOR MAGNETIC FIELD RESEARCH FROM THE GROUND

Our plan to fly a balloon-borne telescope had its origins in 1986, when APL received a University Research Initiative grant from the Air Force Office of Scientific Research to start a center at APL for solar research. One of our first undertakings was to design and build a solar vector magnetograph (SVMG), an instrument that maps the magnetic fields on the surface of the Sun. The SVMG is now in daily operation at the National Solar Observatory at Sacramento Peak in New Mexico.² It is the prototype of the balloon-borne FGE and we are still learning from it.

At Sacramento Peak, our scientific objective is to infer enough information from vector magnetograms at ≈ 2 -arcsec resolution (corresponding to 1000 miles on the Sun) to develop useful physical insight into the structure and evolution of the magnetic fields in sunspot regions. Magnetic flux emergence and disappearance and regions with twisted magnetic fields need to be better understood if we are to make substantial progress in understanding solar flares. A central problem is how to identify the buildup of magnetic energy for flares in an active sunspot region.

Trying to determine solar active-region magnetic fields from ground-based measurements has advantages and drawbacks. We have found that imaging through a narrow-band filter³ and analyzing the results with the weak-field approximation⁴ can give useful temporal and spatial data on magnetic fields,⁵ but the limited spatial resolution imposed by atmospheric blurring makes interpretation of the measurements ambiguous. Nevertheless, on occasion, we get excellent observations. Figure 2 shows a sample of the sunspot magnetic field observations obtained with the SVMG.

We have also obtained observations before and after a number of solar flares. One example was the proton-producing flare of 2 April 1991.⁶ Our observations are among the first to show the development of twisted magnetic fields just one hour before the flare started. A study of a flare recorded at the Big Bear Solar Observatory in California also shows interesting preflare changes in sheared fields.⁷ Recently, we observed the magnetic fields before and after a large flare on 6 February 1993. Analysis of the results is a joint project of the National Solar Observatory and APL.

SCIENTIFIC OBJECTIVES OF THE FLARE GENESIS PROJECT

Solar Flares

The principal aim of the Flare Genesis project is to determine how the fibrous magnetic fields at the solar surface emerge, coalesce, unravel, and erupt in solar flares. The goal is important because magnetic fields are the root cause of flares and most other poorly understood solar activity. The large Flare Genesis telescope, located above the atmosphere, will provide much better sensitivity (see discussion on the need for higher resolution in flare research) for observing magnetic fields than the

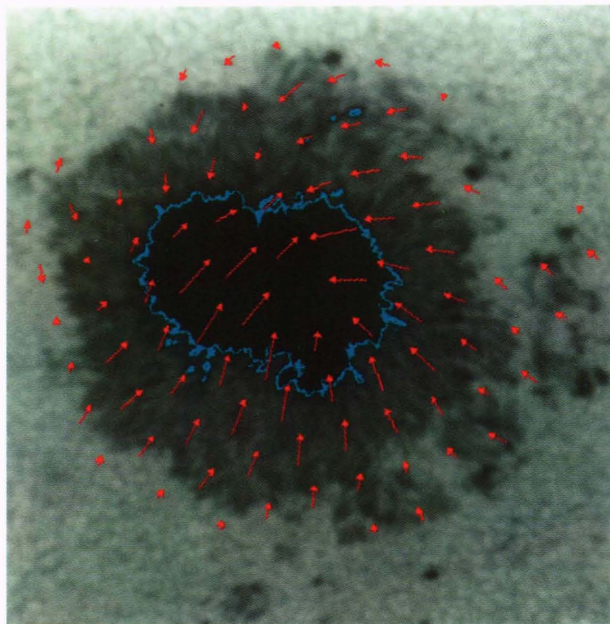


Figure 2. A photograph of a large sunspot on August 16, 1992, taken at Kitt Peak, Arizona, by W. C. Livingston, using the solar vector magnetograph (SVMG). The spot shows a more or less circular umbra (dark center with blue contour) and a well-defined penumbra. The red arrows indicate the pattern of magnetic fields transverse to the line of sight.

SVMG and other ground-based instruments, which are limited by atmospheric blurring. Thus, the project may lead to reliable forecasts of solar activity and the arrival of shocks and atomic particles at Earth.

To understand flares, we must understand the processes that build up and release magnetic energy. We are currently working with theoreticians at several universities to interpret our data. Energy is probably explosively released on the surface of a star via development of an instability in a twisted magnetic field.⁸ Such a field apparently erupts, reconnects, and simplifies, thereby releasing energy for a flare. Two destabilization scenarios are possible. In one, the field is subject to increasing twist until it reaches a critical state beyond which it becomes unstable. Then, electric current sheets form and the field dissipates rapidly into heat and motion.⁹ In the other scenario, strongly twisted fields are a necessary but not sufficient condition for flaring, and some external perturbation is required to destabilize the system.^{10,11} The destabilization may be related to reconnection of the twisted field with *emerging flux*,¹² *evolving flux*,^{13,14} *cancellation of flux*,¹⁵ or *submergence of flux*,¹⁶ all of which, in theory, can induce significant changes in the overlying corona, where flares apparently start. Thus, the FGE will concentrate on magnetic flux developments.

Although the FGE's primary scientific objective is flare research, successful balloon flights should contribute

NEED FOR HIGHER RESOLUTION IN FLARE RESEARCH

Low outlined the basic theoretical guidelines for using magnetic measurements for research on flare energy build-up.²⁵ He showed that the total magnetic energy W in the chromosphere and corona above the plane of measurement (i.e., in $z > 0$) can be written in terms of the three magnetic field components, B_x , B_y , and B_z , measured at the surface ($z = 0$), and μ_0 , the permeability of free space:

$$W \equiv \int_{z>0} \frac{B^2}{2\mu_0} dx dy dz$$

$$= \frac{1}{\mu_0} \int_{z=0} (xB_x + yB_y) B_z dx dy. \quad (1)$$

The difference between the energy given by Equation 1 and the energy contained in a similar but electric-current-free field is the free magnetic energy available for solar flares. To compute the current-free magnetic energy from observations, we replace the measured B_x and B_y in Equation 1 with values computed under the assumption that the field is everywhere current-free. Such fields can be computed from measurements of B_z alone. In ground-based magnetograms, the apparent free energy of an active region that shows sheared features is typically $\sim 10^{32}$ erg, which is only about three standard deviations above the estimated noise level.

The accuracy in magnetic field measurements is related to the uncertainty in estimated energy. The uncertainty ΔW

in the total energy is related to the weakest detectable transverse field strength B_T —which is equal to $(B_x^2 + B_y^2)^{1/2}$ —in a magnetic region with a characteristic dimension L by

$$\Delta W \approx \frac{\sqrt{2}}{2\mu_0} (B_T)^2 \frac{L^3}{\sqrt{N}}, \quad (2)$$

where N is the number of independent measurements contributing to the estimate of the integral in Equation 1. For a magnetograph with a magnetic sensitivity B_T of approximately 150 G and a pixel array greater than 100×100 with 2.5-arcsec pixels, where L is approximately 2×10^{10} cm and $N = 10^4$, Equation 2 gives $\Delta W \approx 10^{32}$ erg, in agreement with the uncertainty found in typical ground-based measurements.

Equation 2 shows that increasing the number of independent measurements through enhanced spatial resolution is essential to achieving useful magnetic energy resolution. Increasing the spatial resolution increases magnetic sensitivity in another way, because the polarization signals used to infer the fields will not be mixed with light from field-free surroundings. The FGE, with 1024×1534 0.1-arcsec pixels, should reduce the 3-s limit for detection of free energy conversion. We estimate the limit at $< 10^{29}$ ergs over the $1.7\text{-arcmin} \times 2.5\text{-arcmin}$ field of view. Many flares with magnetic energy needs above this level should occur during a 2-week flight of the FGE.

broadly to a better understanding of many other features on the Sun even when solar activity is low. Examples follow.

Sunspots

The Flare Genesis vector magnetograph can address such questions as these: What is the radial and vertical distribution of the magnetic field in a spot? What is the relationship between the magnetic field and fine-scale features such as the dark fibrils of the penumbra? And finally, why do spots appear at all?

Photospheric Flows

The FGE can measure the surface motions in magnetic fibrils and sunspots to determine a total flow field and possibly answer the question of whether subsurface flows or visible surface flows control the migration of magnetic features. We also hope to find out how large-scale flows are related to magnetic energy buildup.

Coronal Heating

There will be several X-ray telescopes in space during our balloon flights. By comparing our images with pictures of the Sun's X-ray emissions (Fig. 3), we should be able to determine precisely how the X-ray features relate to the underlying vector magnetic field structures.

Areas of the solar atmosphere that emit X-rays are being heated to several million degrees. We do not understand how the heating occurs, but many physicists believe that the continuous churning of the magnetic fields produces electric currents that cause heating.¹⁷ Joint observations of fields and flows by the FGE and of X-ray emissions by a satellite-borne telescope could show just how energy concentrates in the solar corona and settle the important and long-standing question about the origin of coronal heating.

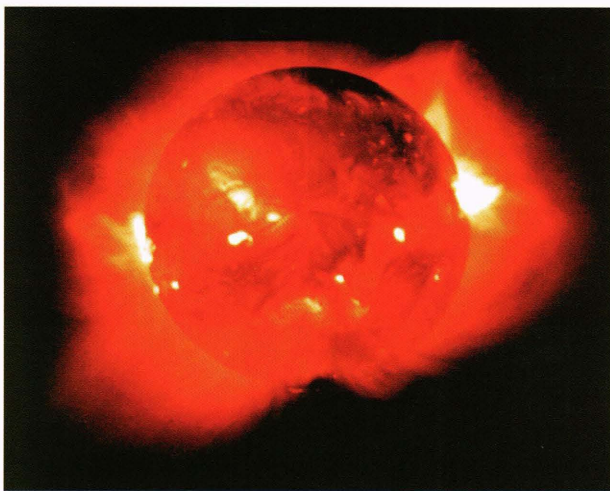


Figure 3. An image of the solar corona's X-ray emissions on 26 August 1992, taken by the X-ray telescope aboard the Japanese Yohkoh satellite observatory. The bright regions are the hottest, about 3×10^6 K. Heating is attributed to electric current dissipation over sunspot regions.

Table 1 details how the data obtained with the FGE relate to the targeted solar measurement goals. Table 2 details the capabilities of the FGE.

INSTRUMENT DESCRIPTION

Design Study

Drawing on our experience with the magnetograph in New Mexico, APL initiated a design study of a balloon-borne SVMG. The study showed that a balloon-borne instrument is feasible, but presents significant challenges. We believe that we can overcome the principal difficulties, such as thermal control and precise pointing, by drawing on the experience of other ballooning groups, particularly those at the Harvard/Smithsonian Center for Astrophysics¹⁹ and the Air Force Phillips Laboratory.

In the design study, we looked at the effects of image motion, gravity, and temperature on a balloon-borne telescope to determine whether the FGE can maintain the desired resolution of ≈ 0.2 seconds of arc. The principal conclusions of the study are as follows:

1. With an image motion compensator (IMC), sufficient image stability can be maintained at the FGE focal plane to allow magnetic mapping at a 0.2-arcsec resolution, despite the continual pendulation of the FGE's gondola and the harsh environment.
2. A complete FGE, including onboard data recorders, can be built within the customary power and weight limits for balloon flights.
3. The needed optical components either exist or can be obtained commercially in less than six months.
4. Most of the mechanisms needed are similar to those used in our SVMG at Sacramento Peak, and their incorporation into the balloon-borne instrument should pose no serious problem if they are operated in a temperature-controlled, pressurized chamber.
5. The FGE can achieve a polarization sensitivity of 4 parts in 10^4 .²⁰ Our theoretical work shows how magnetic field parameters can be inferred from the polarization measurements.²¹

New Technology

The Flare Genesis project is only one of many astronomy projects now benefiting from the end of the Cold War and the consequent release of valuable equipment and new technology. In the past year, we have obtained many of the high-technology devices needed to carry out the project. Through the generosity of many organizations, we will be using much better equipment than we had expected.

The Strategic Defense Initiative Organization transferred the former Starlab telescope to the project. The primary mirror is 80 cm in diameter, making it one of the world's largest mirrors for solar research. It is now being modified to meet our requirements. Figure 4 is an artist's conception of the modified telescope and a smaller target selector telescope (TST) in the gondola at float altitude over Antarctica.

The Starlab telescope body is made of graphite-epoxy fiber and the mirrors are ultra-low-expansion glass. The dimensions of both materials are stable over wide

Table 1. Targeted solar measurements.

Targeted measurements	Observables	Rate	Science summary
Evolution of magnetic shear	$\mathbf{B}^{\text{ph}}, \mathbf{V}^{\text{ph}}, H_{\alpha}$	$200 d^{-1}$	Determine how shear develops; compare shear changes pre/postflare.
Flare mode	$\mathbf{B}^{\text{ph}}, \mathbf{V}^{\text{ph}}, H_{\alpha}$	$2 h$	Perform rapid cadence through flare to detect field changes.
Magnetic energy	\mathbf{B}^{ph}	Pre/post flare	Compare energy calculations before and after flare to test theory of energy conversion.
Electric currents	$\mathbf{B}^{\text{ph}}, \mathbf{V}^{\text{ph}}, H_{\alpha}$	$20 d^{-1}$	Derive vertical current density; infer current distribution; locate current sheets.
Active region (AR) magnetic field	$\mathbf{B}^{\text{ph}}, H_{\alpha}$	$200 d^{-1}$	Study interaction of \mathbf{B} , \mathbf{V} and their role in generating small-scale structures; detail connections with chromospheric \mathbf{B} , \mathbf{V} ; look for flux emergence, submergence, cancellation.
Vertical structure of AR magnetic field	$\mathbf{B}^{\text{ph}}, \mathbf{B}^{\text{ch}}, H_{\alpha}$	$10 d^{-1}$	Measure \mathbf{B} in photosphere, chromosphere; determine vertical variation of angular shear; assess evidence of magnetic canopy.
Sunspot field and dynamics	$\mathbf{B}^{\text{ph}}, \mathbf{B}^{\text{ch}}, \mathbf{V}^{\text{ph}}, \mathbf{V}^{\text{ch}}, H_{\alpha}$	$20 d^{-1}$	Measure sunspot field in photosphere and chromosphere, radial and vertical field distribution, field of umbral dots, Evershed flow.
Filaments	$\mathbf{B}^{\text{ph}}, \mathbf{V}^{\text{ph}}, H_{\alpha}$	$5 d^{-1}$	Observe formation by flux cancellation, difference in fields of quiet and active region filaments; compare \mathbf{B} with models.
Flux tubes	$\mathbf{B}_1^{\text{ph}}, \mathbf{B}_2^{\text{ph}}, \mathbf{V}^{\text{ph}}, H_{\alpha}$	$2 d^{-1}$	Measure \mathbf{B} in two lines of same multiplet to derive flux tube physical properties.

Note: Adapted from Reference 18.

\mathbf{B}^{ph} and \mathbf{V}^{ph} are the magnetic field and velocity field, respectively, of the solar photosphere, which is the brilliant solar surface. \mathbf{B}^{ch} and \mathbf{V}^{ch} are the corresponding fields for the chromosphere, the thin atmosphere just above the photosphere. H_{α} refers to the deep red light emitted by hydrogen atoms in the chromosphere. H_{α} images show the finest details of the structure of the gaseous clouds of the chromosphere.

Table 2. Flare Genesis Experiment capabilities.

Spatial resolution: Limited by diffraction to 0.2 arcsec (140 km at the Sun)

Spectral resolution: 0.014-nm passband tunable over spectral line profiles with repeatability to 1×10^{-4} nm

Wavelength range: 610–660 nm

Field of view: 100 arcsec \times 150 arcsec

Detector: Charge-coupled device, 1024×1534 unocculted pixels

Exposure interval: 190 s for one magnetogram, 240 s for two interleaved magnetograms

Data products: Time series of vector magnetograms at various wavelengths, vector velocity and intensity in the photosphere and chromosphere

Data storage capacity: 50 Gbytes = 10 tape cassettes with 1600 images each = 260 magnetograms, without data compression, per tape in a 10-cassette loader (based on a 100 arcsec \times 150 arcsec field of view)

Telemetry downlink: 1 Mbit s^{-1} (occasional) for target selection, 1 kbit s^{-1} (nearly continuous) for commands and status checks

Detectable magnetic field: $B_z = 10^{-4}$ – 10^{-3} T, $B_{x,y} = 0.5 \times 10^{-2}$ – 1.0×10^{-2} T (depends on trade-offs in data processing); B_z is the line-of-sight component

Velocity sensitivity: ≈ 5 m/s

Intensity sensitivity: $\Delta I/I = 4 \times 10^{-4}$ single pixel, 10^{-3} pixel-to-pixel

Spectral lines: 1) 630.25 nm, Fe I, Landé $g^a = 2.5$

2) 656.28 nm, H I (H_{α}), Landé $g^a = 1.045$

3) 638.78 nm; 642.28 nm; 645.81 nm, all clean continua

4) Other lines selectable between 610 and 660 nm

^aRelative magnetic field sensitivity

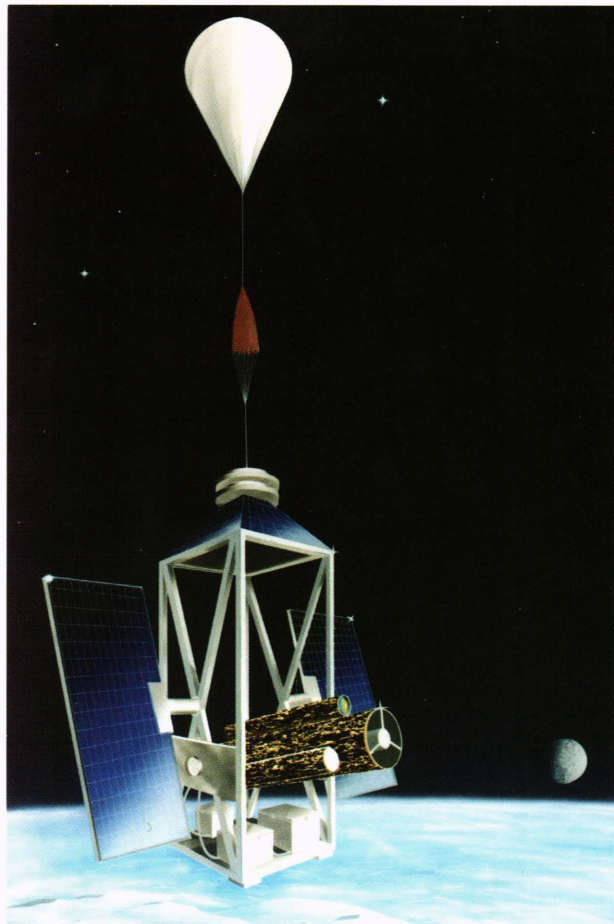


Figure 4. Artist's conception of the Flare Genesis Experiment over Antarctica. The height of the gondola will be ≈ 18 ft; the main telescope has a 32-in. aperture and a 5-arcmin field of view; the target selector telescope has a 4-in. aperture and a 1° field of view.

temperature ranges. Therefore, we expect to be able to maintain diffraction-limited performance despite the large difference between the temperature at which the mirrors were made and tested and the operating temperature in the stratosphere.

Figure 5 is a schematic drawing of the modified telescope optics and the optical instruments behind the focal plane. The key high-technology elements are the lightweight honeycomb, ultra-low-expansion primary mirror; the single-crystal silicon secondary mirror; the graphite-epoxy mirror cell and tube; liquid-crystal polarization analyzers; a tunable lithium niobate etalon filter;³ two image motion compensators; and the fast 1024×1534 electronic camera at the focal plane. The system also includes the on-board FORTH-language Reduced Instruction Set Computer (FRISC) and a star tracker. We briefly describe each of these components.

Ultra-Low-Expansion Materials

The lightweight mirror and graphite-epoxy structure provide high thermal stability so that the optical figure, which should be accurate to $\frac{1}{20}$ of a wave, is maintained over a wide temperature range. The low weight also facilitates recovery. Although the 26×10^6 -ft³ helium

balloons used for long-duration flights can lift almost 5000 lb to our required altitude of 125,000 ft, a light, compact payload means that, if necessary, only two men in a small airplane can easily recover the mirror. The mirror weighs 110 lb—about one-third the weight of a solid mirror.

Both the primary and the secondary mirrors will be coated with silver and several protective layers so that they reflect $\approx 97\%$ of the incident solar energy throughout the spectrum. About 500 W will strike the primary, secondary, and heat-dump mirrors; we expect that the heat absorbed at each one can be removed with heat pipes. A heat-dump mirror reflects 90% of the sunlight back out of the telescope.

A single crystal of silicon will be used for the secondary mirror material because silicon takes a very smooth polish and has a high ratio of conductance to thermal expansion. Therefore, absorbed solar energy can be removed with minimum mirror distortion. The mirror will be polished to the needed precision with technology developed for laser fusion research.

Liquid-Crystal Devices

Until recently, liquid-crystal devices were analogous to simple switches: they either passed light or they blocked it. It was difficult to manufacture a device that allowed the degree of retardance—the amount of light passed—to be set precisely because most liquid crystals were insensitive to voltage, except over a small range. Now, we are able to obtain devices that maintain a precise degree of retardance for each voltage setting. New liquid-crystal recipes stretch out the voltage response so we can obtain the four states of retardance we need to completely characterize the polarization state of the sunlight at each point in the field of view.

Fabry-Perot Etalon

An etalon is a wavelength standard. Our etalons consist of a 75-mm-dia. wafer of lithium niobate polished to a flatness of about $\frac{1}{100}$ of a wave. Normally, they transmit light at a fixed wavelength, but we applied indium-tin oxide coatings to the crystal faces to make them electrically conductive. Connecting the etalon to a voltage source then impresses an electric field on the lithium niobate crystal, altering its index of refraction and, thus, the optical path in the Fabry-Perot cavity. As a result, the wavelength of light passed by the filter is proportional to voltage. On the first flight, the filter will have a passband of less than 0.020 nm and will be tunable to any wavelength between 580 and 680 nm.

J. Miragliotta of the Materials Science Group in the APL Research Center made extensive dye laser tests of several etalon filters. The best etalon has a 0.014-nm bandwidth, and should improve magnetic field sensitivity on later flights.

Image Motion Compensator and Silicon Retina

The IMC system senses unwanted translational motion of the images and reduces or removes it with an agile tip-tilt mirror. For the FGE, the closed-loop bandwidth of the

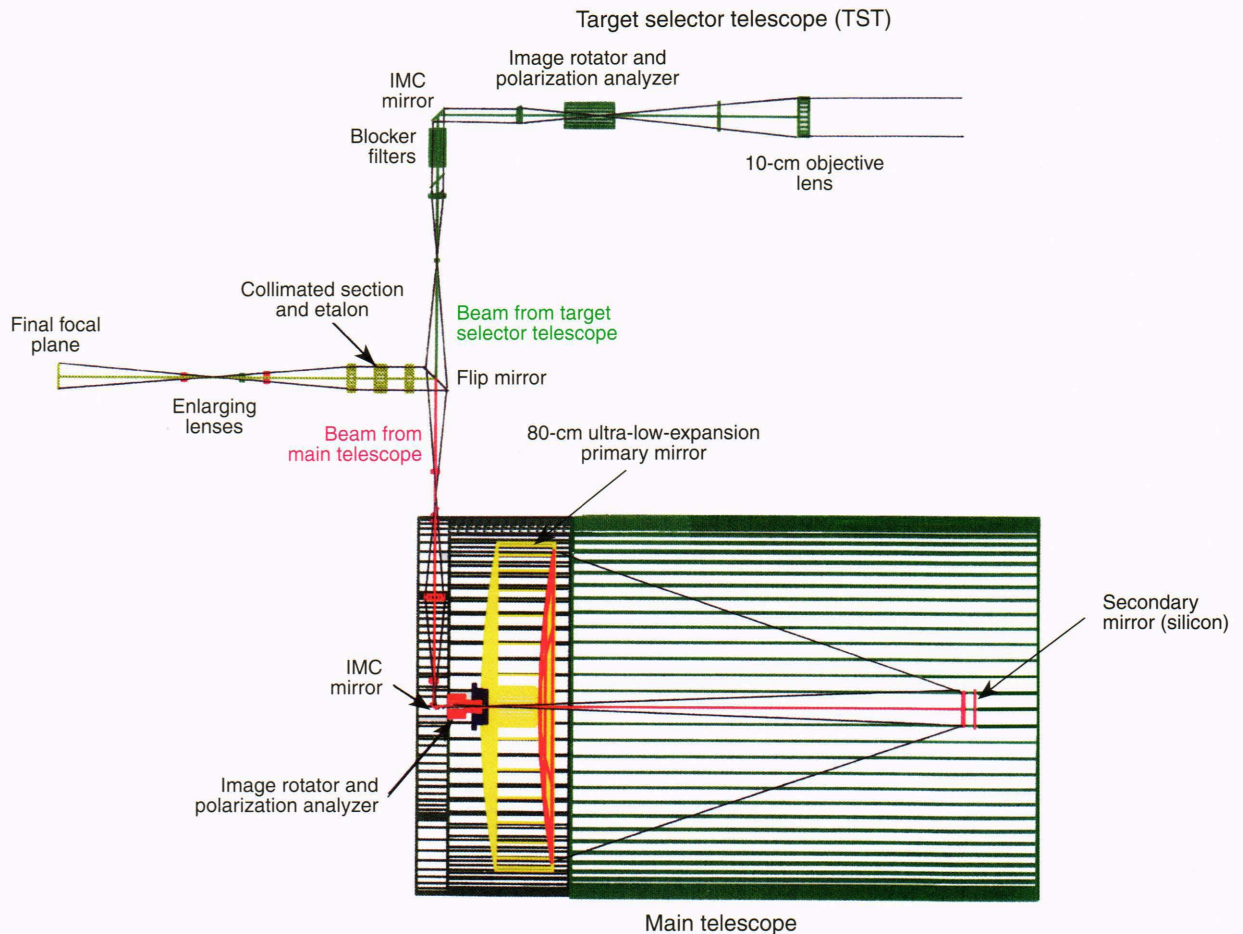


Figure 5. Optical schematic of the Flare Genesis Experiment (FGE) behind the focal plane (some fold mirrors are not shown). Key components include a thermally stable, lightweight, ultra-low-expansion (graphite-epoxy) mirror; a single-crystal silicon mirror with very low distortion; liquid-crystal polarization analyzers that pass a precise amount of light at a certain voltage; a Fabry-Perot etalon filter that can be tuned to pass specific wavelengths of light; and image motion compensators (IMC's), which minimize translational motion of the images.

IMC must be greater than 50 Hz to provide adequate disturbance rejection. A digital-sampled-data IMC would have to sample at a rate of around 500 frames per second to meet this bandwidth requirement. Such a digital system can be implemented with a small, high-speed charge-coupled device (CCD) camera and custom digital hardware,²² but we have chosen instead an analog servo-loop approach based on a novel image position sensor.

The analog approach has significant advantages over digital systems in weight, power, simplicity, reliability, and performance. Many image motion sensors require a bright or dark feature before they will track and remove motion at the focal plane. But the main solar telescope does not provide an image of the bright whole solar disk, nor can we expect to find conveniently placed sunspots to track. The Computer Science and Technology Group in the APL Space Department is developing a series of novel image position sensors that combine analog computations and signals from a photodetector array to continuously compute image position. All image sensing and computations are carried out in a single microchip which produces a video image as well. We call this device a video computation (VC) chip.²³ The video output has prov-

en to be very helpful during system debugging and integration. The VC chips use neuromimetic analog current-mode computations, and in some cases, we implement a silicon retina as the detector array.

The first version of a VC chip now operates in the sunspot tracker (IMC) in the SVMG at Sacramento Peak. Figure 6 shows a recording of the motion of a small sunspot's image with and without the tracker operating. With the tracker operating, the residual root-mean-square deviation of the spot position was 0.1 arcsec. This VC chip requires a bright or dark feature, such as a sunspot, to correct the motions.

For the FGE, we are developing a correlation-based position sensor which will track subtle, low-contrast features such as solar granules. This detector will probably require a silicon retina for image preprocessing, so we refer to it as a retinal computation chip (RVC). The balloon environment, although relatively benign, is not disturbance-free, so the success of the Antarctic flights depends on successful implementation of the RVC chip.

We have also developed for the FGE a tip-tilt mirror with magnetostrictive actuators. The IMC in the ground-based SVMG has always suffered from dynamic range

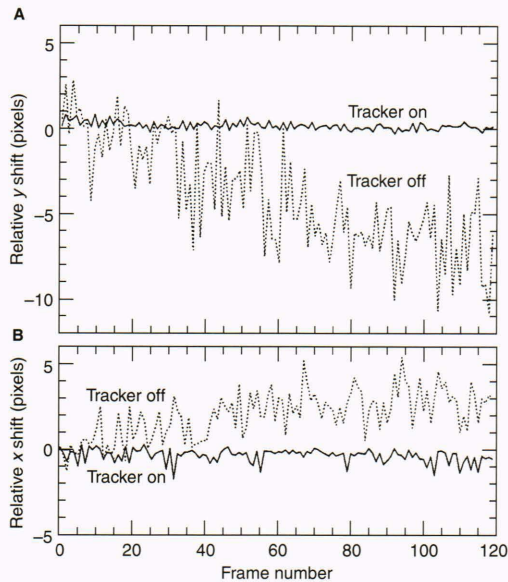


Figure 6. Sunspot image motion with and without the IMC spot tracker operating. The tracker removes motion at the focal plane. **A.** y-axis result. **B.** x-axis result. Data from 16 August 1992.

restrictions because of the limited throw (less than 100 arcsec) of its piezoelectrically driven tip-tilt mirror. Our new tip-tilt mirrors have a wide bandwidth (first bending mode at 200 Hz with a damping ratio of 0.25) and achieve a throw of ± 600 arcsec in the TST and ± 1200 arcsec in the main telescope. The large throw is necessary because of the high angular magnifications seen at the tip-tilt mirrors. We expect that the actual jitter of the telescope will not exceed ± 10 arcsec, but the tip-tilt mirrors operate at small images of the entrance pupil, and the angular deviations are magnified as the pupil is demagnified.

We were also forced to turn to the relatively new technology of magnetostrictive actuators because, at the planned altitude of the FGE, the high-voltage actuators we use on the ground would have to be pressurized to avoid electrical arcing. The new tip-tilt actuators can be driven with only ± 15 V, so they will be completely immune to arcing.

Figure 7 shows the positions of the IMC mirrors and the other focal-plane devices, which are arranged compactly at the back of the main telescope. Either of the two beams, from the TST or the main telescope can be sent through the etalon filter to the electronic camera.

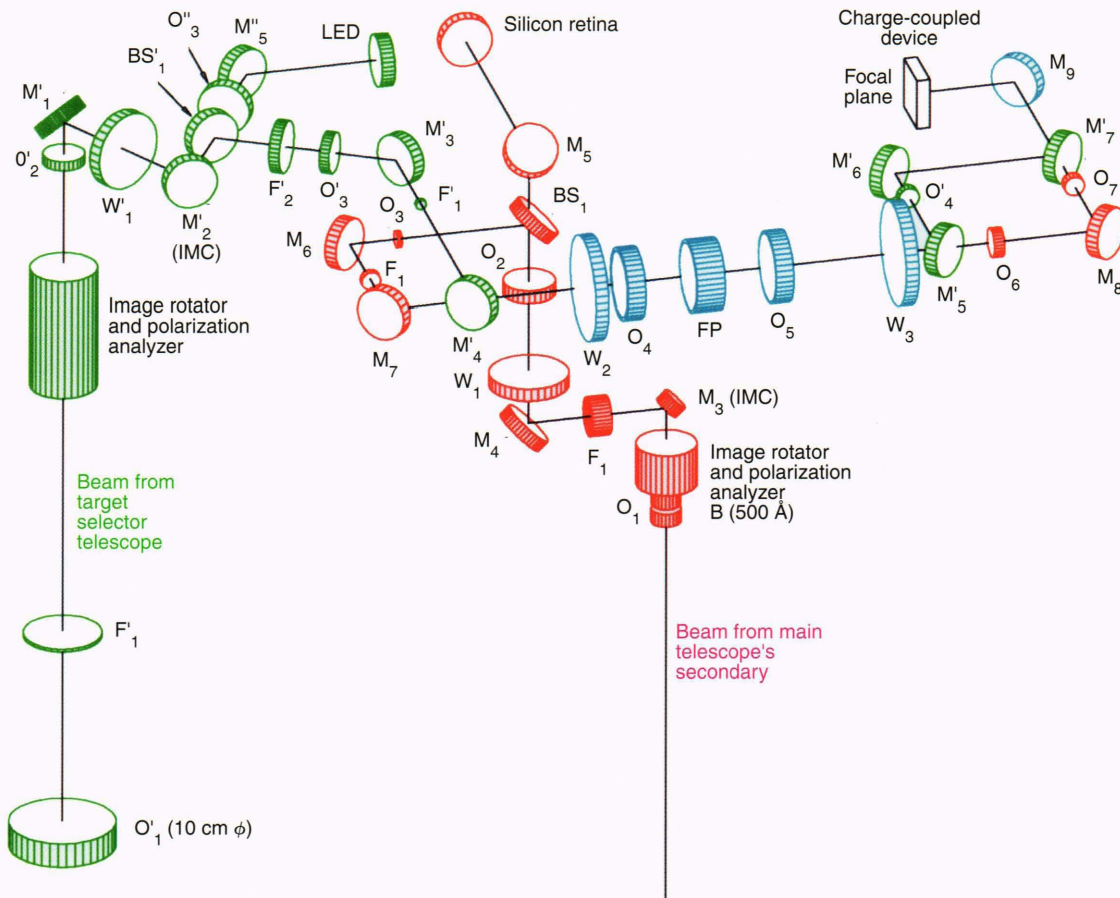


Figure 7. Layout of windows (W_i), mirrors (M_i), objective lenses (O_i), field lenses (F_i), beam splitters (BS), and electro-optic elements (such as the Fabry-Perot etalon, FP) on the optical bench attached to the rear of the main telescope. Optics for the high-resolution beam from the main telescope are red, those for the target selector telescope (TST) are green, and shared elements are blue. The TST optical element names are primed. M_2 and M_3 are the image motion compensator (IMC) mirrors for the TST and main beam, respectively.

High-Speed Electronic Camera

High-resolution solar research relies on array detectors of CCD's (i.e., electronic cameras) with millions of sensors or picture elements (pixels). The Flare Genesis CCD camera has over 1.5 million pixels. The APL Computer Systems Services Group is building CCD camera support electronics capable of handling a data rate of 20 Mbytes per second. The CCD camera includes a microprocessor for diagnostics and shutter control. Data from the camera are sent by fiber optics to the APL-developed FRISC.²⁴

Star Tracker

Even though the Sun will always be above the horizon, the sky at 125,000 ft will be as dark as it is during a solar eclipse, when stars can be seen with the naked eye. The mission of the FGE is to observe the Sun, but the balloon gondola will carry a star tracker too, pointed at the dark sky 90° from the Sun.

The star tracker was developed by the Space Department's Guidance and Control Group for the Army Topographic Service. It was to fly on the Space Shuttle and identify and track the stars at any point in the heavens, as an aid to precision mapping. It has a built-in computer which can recognize any constellation of five stars inside any 10° field of view. It continually compares the stars detected by its camera to a catalog of 9000 stars and computes the right ascension and declination of its line of sight to within 4 arcsec.

Far more sensitive than the eye, the star tracker will continuously report on the apparent position of the stars and thereby measure the swaying or pendulation of the gondola. We do not expect the pendulation to exceed 1° in 20 s, but even that small motion will smear the solar images unless it is corrected inside the telescope. Signals from the star tracker will drive image-rotating prisms in the two solar telescopes which will move to cancel any rotation of the field of view.

The flight of the FGE will provide a nearly ideal test of the star tracker, which can no longer find a place in the Shuttle's manifest. In effect, it is another example of Cold War hardware now being used in scientific research.

FLIGHT PLAN

The first flight of the FGE will test the telescope pointing scheme, which means that it must be able to dump unwanted azimuthal momentum into a flywheel between the gondola and the balloon cable. The test flight will take place in New Mexico and will last for less than a day. Only the TST will be aboard. A wooden facsimile will represent the main telescope, so that it will not have to face the rigors of flight until the first scientific mission.

In December 1994, the entire experiment will fly in Antarctica. Except for the first twenty hours, it will be out of radio contact and will have to react automatically to solar activity. Since the onboard data storage tapes will be filled after ten days if images are accumulated at the rate of about one every four seconds, our collaborators at Sacramento Peak have written computer software that directs the FGE to examine the state of the Sun period-

ically and rank the science objectives. For example, if a large sunspot is at the center of the solar disk, then a code to map the motions and magnetic fields in the penumbra might be chosen automatically.

Table 3 outlines this Autonomous Observing Program (AOP). Many details, such as initial pointing and checkout of the telescope, have been omitted from the table, but virtually all operations must be foreseen. Resources in Antarctica are so limited that we cannot be sure that we will have any contact with the experiment except for minimum health and safety data. The AOP is already able to select sunspots, flares, and other features from typical solar images (Fig. 8).

After one circumnavigation of the South Pole, the FGE will drop to the ice under a parachute. We will try to choose a landing point that is accessible to helicopters or LC-130 Hercules aircraft, which can bring the entire payload back to McMurdo in one piece. If the package lands at a high elevation, we will have to land a Twin Otter airplane equipped with skis near it and take away only what the airplane can carry. The data tapes have first priority, followed by the primary mirror.

Table 3. Autonomous Observing Program.

1. Select area for study on basis of full-disk images from the target selector telescope (TST).
2. Select timing sequence on the basis of science program (e.g., flares, magnetic field evolution, oscillations, granule proper motion).
3. Select wavelength: adjust blocker filter and voltage to the etalon.
4. Adjust etalon tilt to correct for solar rotation Doppler shift.
5. Select exposure time.
6. Command main telescope to desired azimuth and elevation.
7. Turn on image motion compensator (IMC) and check contrast (focus) of IMC images.
8. Select voltages for liquid-crystal devices (2) in the polarization analyzer on the basis of science, temperature, and apparent angle of the solar axis.
9. Command dark-current and gain exposures by charge-coupled device (CCD) camera.
10. Start exposure sequence.
11. Dump data to Exabyte tapes.
12. If science program allows, interrupt exposure sequence once per hour to verify pointing and record full-disk images from the TST.
13. End sequence, obtain new darks and flats.
14. Verify focus and instrument health.
15. Review science priorities in light of solar activity, completed observations, and expected time and tape remaining. Go to step 1.

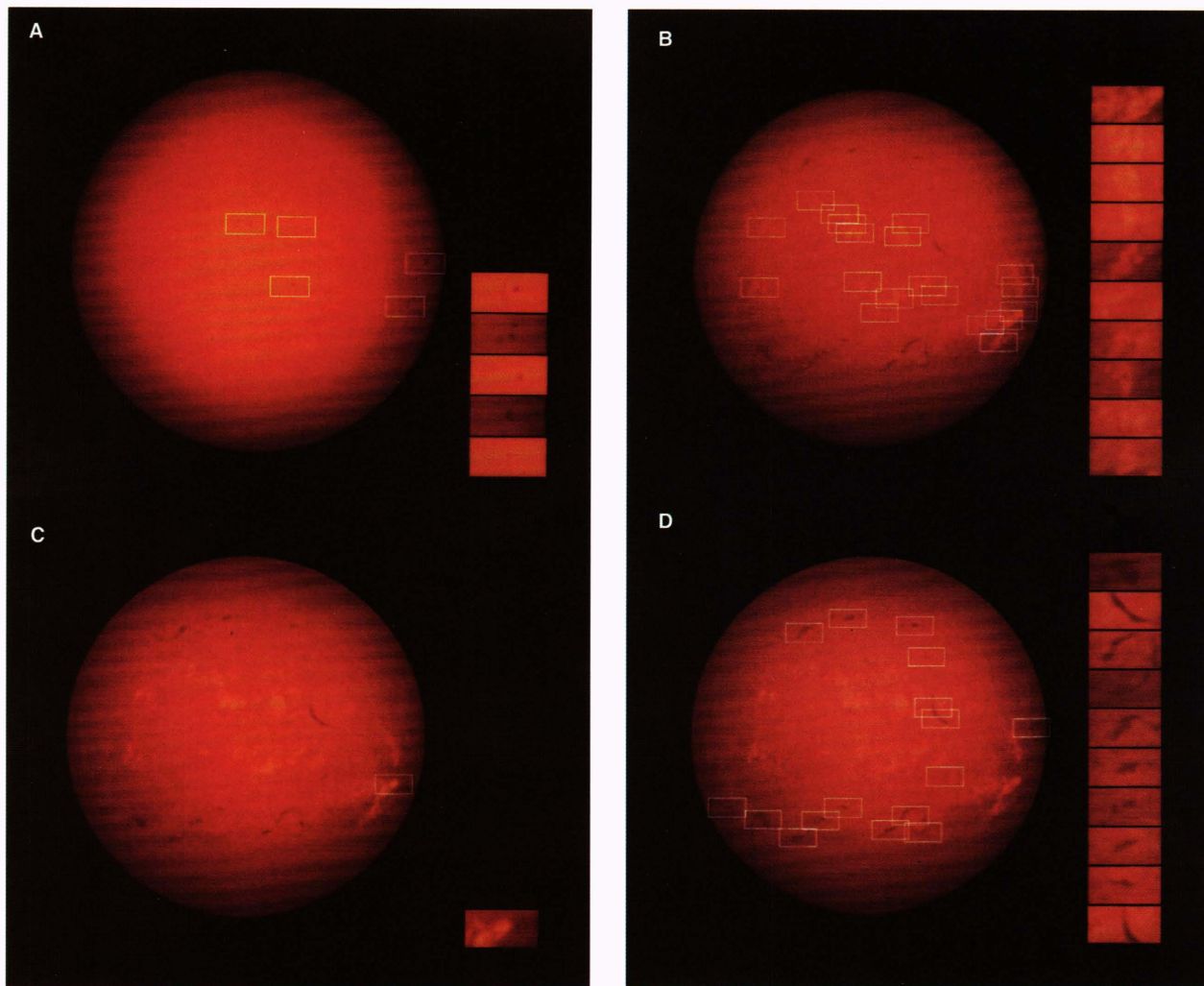


Figure 8. **A.** An image of the Sun showing the photosphere, where sunspots are the most prominent features. The photograph was taken at the National Solar Observatory through a telescope similar to the target selector telescope. The Autonomous Observing Program (AOP) has identified five sunspot regions and listed them in order of decreasing sunspot area. **B.** A photograph of the chromosphere, which is the thin layer of the atmosphere just above the photosphere. Most of the bright features are plages, regions of enhanced magnetic fields, but the brightest feature is a flare. **C.** The AOP has removed the natural darkening of the solar disk near the edges and has discovered the flare. **D.** Solar filaments identified by the AOP. Since a filament at a site that will flare soon will darken and twist about, the program selects the darkest filament, points the main telescope at it, and collects data until a flare occurs.

CONCLUSION

The FGE is presently being assembled at APL. We have purchased and tested most mechanisms, such as image rotators, and we are integrating the mechanism control computers with the onboard instrument control computer. The experiment will be mated with the gondola at the Air Force Phillips Laboratory facilities at Kirtland AFB and test flown near there. If the pointing system performs as planned, then the flight in Antarctica has an excellent chance to achieve major breakthroughs in solar research.

The Flare Genesis project, which can trace its roots to the AFOSR University Research Initiative grant, can lead to a revolution in understanding flares and the structure of sunspot regions. The recent SVMG observations indicate that there are clear signatures of impending flares in the vector magnetic fields. What is needed now is the long, sharp look that can be provided in this millennium only by the Flare Genesis Experiment.

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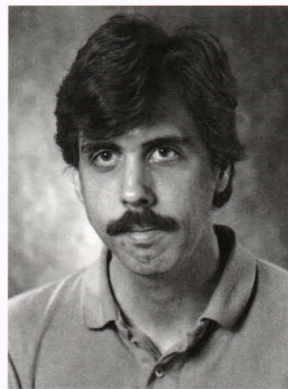
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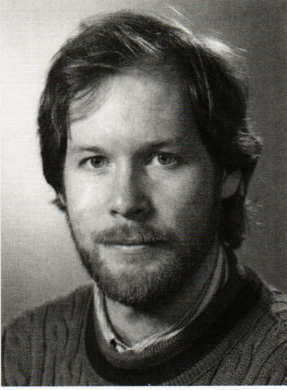
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