



MISSIONS TO THE SUN

Almost all space disturbances start at the Sun. David Rust examines how we study our most important star and what can be learned from the data retrieved from solar instruments. BY DAVID M. RUST

W

e rely more every day on systems that operate in space. They provide better communications, navigation, and defense. Yet space is not a dark and passive void. Space between the Sun and the planets is frequently laced with atomic particle radiation and shaken by storms. The storm clouds contain electrons and protons, and they take their twisted shapes from the magnetic fields that spring from the Sun. This is our space environment, and solar researchers are relying on better telescopes to understand how the Sun affects it.

Almost all space disturbances start at the Sun. When a TV network satellite recently stopped broadcasting, it was because of electrons energized by solar wind streams. When Skylab, man's first space station, fell into the atmosphere before it could be retrieved, it was because the Sun was more active than anyone had forecast. And, when the power from solar panels on an interplanetary mission suddenly dropped, it was because of damage by solar protons.

In deep space, beyond Earth's protective magnetosphere, solar atomic radiation—mostly energetic protons—can be very dangerous. Unless future astronauts can be warned of impending solar storms, manned voyages to Mars may be unthinkable. Given adequate warning, Mars-bound astro-

Figure 1. The Sun as seen with an x-ray telescope.

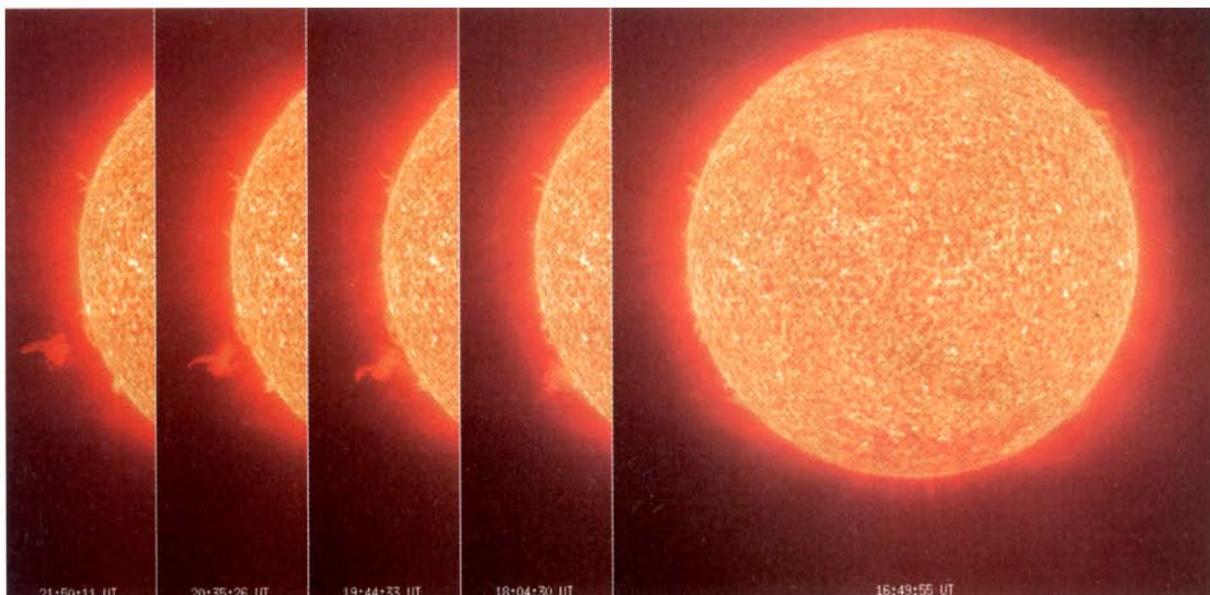


Figure 2. The Sun in light emitted by atomic helium at 304 Å. Photo taken on February 11, 1996, by the Extreme-ultraviolet Imaging Telescope on board SOHO.

nauts can find temporary shelter behind thick aluminum plates, but they can't spend the whole trip there. They need reliable warnings without too many false alarms, and the magnitude of the hazard should be neither underestimated nor overestimated.

Solar researchers are now focused on future space missions and new technology needed to meet the challenges posed by manned travel to Mars and by society's heavier reliance on space systems for down-to-Earth goals. Their objective is a better understanding of the Sun and more accurate forecasts of solar activity. Success will reduce the risks and costs of using space and provide a deeper understanding of fundamental processes that occur throughout the universe.

Solar research in the space age

The first solar telescopes in space were really just x-ray sensors.¹ They had no imaging capability, but

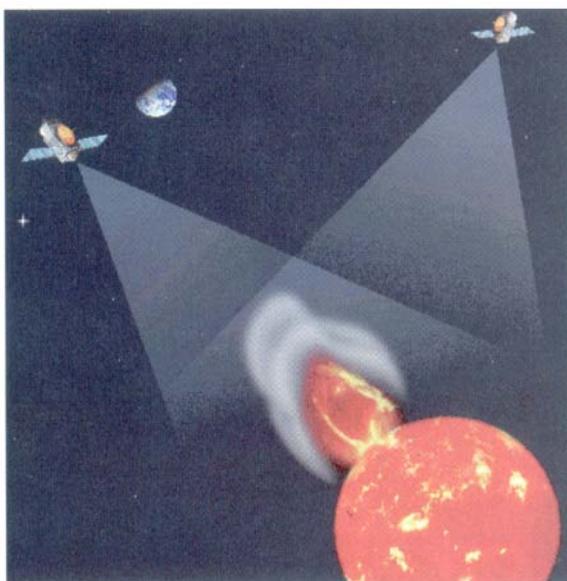


Figure 3. The Solar Terrestrial Relations Observatory will have two to four spacecraft well separated from Earth for a better perspective on solar hazards.

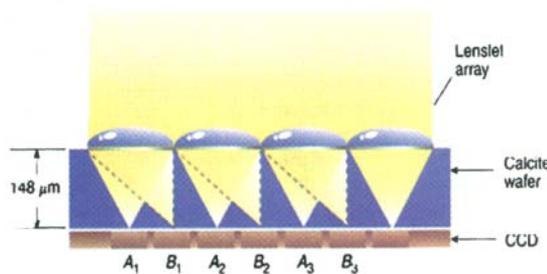


Figure 4. A compact polarization detector. The ordinary rays focus on the A array of pixels and the extraordinary rays (dashed lines) focus on the B array.

they did show how dramatically the Sun's x-ray brightness can change from minute to minute. The x-ray bursts are called solar flares, and today the most relied-on warning of an impending space storm is a sudden, thousand-fold increase in the Sun's x-rays. Atomic particle radiation hazards in space, outside Earth's magnetosphere, sometimes increase to life-threatening levels a few minutes after a flare. But the problem is that predictions of radiation levels and of magnetic storm intensity, which peaks three or four days later and causes problems inside the magnetosphere, are notoriously unreliable. We simply do not understand solar flares or the sequence of events on the Sun leading up to them. Nor do we understand what happens in the solar atmosphere to increase the energy for flares. Finally, we generally don't know what happens between the Sun and Earth to guide or deflect the energy of a flare toward or away from us.

In the 1960s, it was realized that telescopes were needed that could form images of the x-ray emitting areas. The resolution of the solar x-ray telescopes gradually improved from several minutes to several seconds of arc. The Skylab images, taken in 1973-74, were landmarks in solar research.² They achieved 2 arcsec resolution, which is equivalent to 1500 km at the solar surface. But Skylab lasted only nine months, and eventually the great observatory burned up in the atmosphere because of the storms created from the very object it had been designed to probe.

Other orbiting solar telescopes have come a long way since the first robot Orbiting Solar Observatories were launched in the 1960s. The Japanese Yohkoh (sunbeam)² x-ray telescope, which was launched in 1991 and is still operating today, has produced millions of images, each with a million pixels. Figure 1 shows a typical image from Yohkoh. This observatory uses a grazing incidence telescope based on the Woltjer design. It is relatively large, and more compact optical schemes based on multi-layer mirrors used at normal incidence will be at the heart of future x-ray telescopes.⁴

X-ray telescopes generally give little spectral information. One scheme to overcome this problem is based

on the highly successful slitless spectrograph flown on the Skylab mission. The instrument described by Moses⁵ will have orthogonally mounted slitless telescopes. This will remove some ambiguities of interpretation that appeared with the Skylab data. It will now be much easier to distinguish between Doppler shifts in emissions from ejected gases and unusual emission of spectral lines that appear only in very hot flares.

SOHO

The Solar and Helio-spheric Observatory (SOHO)⁶ was launched in December 1995, and is providing the most comprehensive record of solar activity yet. The \$1.1 billion spacecraft carries a dozen telescopes that capture solar x-rays, ultraviolet, and visible light. Figure 2 shows how the Sun looks in the extreme ultraviolet light emitted by helium atoms. The sequence depicts an eruption of a magnetic filament from the chromosphere, the 10,000°C region at the base of the Sun's atmosphere. The sophisticated telescopes aboard SOHO allow researchers to study the temperature, density, magnetic fields, and motions of the solar gases.

Perhaps the most compelling of the SOHO images come from the Large Angle Spectroscopic Coronagraph

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(LASCO) telescope.⁷ LASCO incorporates the latest improvements in ultra-high-polish mirrors. A coronagraph must have optics that scatter almost none of the direct sunlight in order to reveal the faint features seen in the figure. They are only one-billionth of the solar disk brightness.

A spectacular image from LASCO can be found on the Web at sohowww.nascom.nasa.gov/gallery/LASCO. It shows a massive and twisted magnetic filament moving outward into space at 500 km/sec. The ejection shown will miss Earth, but similar ejections are aimed at us

every day. Many of them cause destructive magnetic disturbances that heat the upper atmosphere and sometimes disrupt electric power networks.

The LASCO clearly shows what solar ejections heading away from both Sun and Earth look like, and by following them, researchers can test theories of the fundamental physical processes taking place. But, because the light from the ejections is so faint, we cannot see the clouds headed directly toward Earth. The solar disk light overwhelms their light, which is just sunlight scattered by a thin cloud of electrons.

There is increased emphasis today on the magnetized clouds of electrons and protons, which are called coronal mass ejections (CMEs), as seen in the LASCO images. While an x-ray flare is a good indicator of the onset of a storm, researchers now believe much better forecasts could be made if the CMEs could be tracked between the Sun and Earth. The LASCO images show what could be achieved by a coronagraph operating at a vantage point well separated from Earth (see Fig. 3).

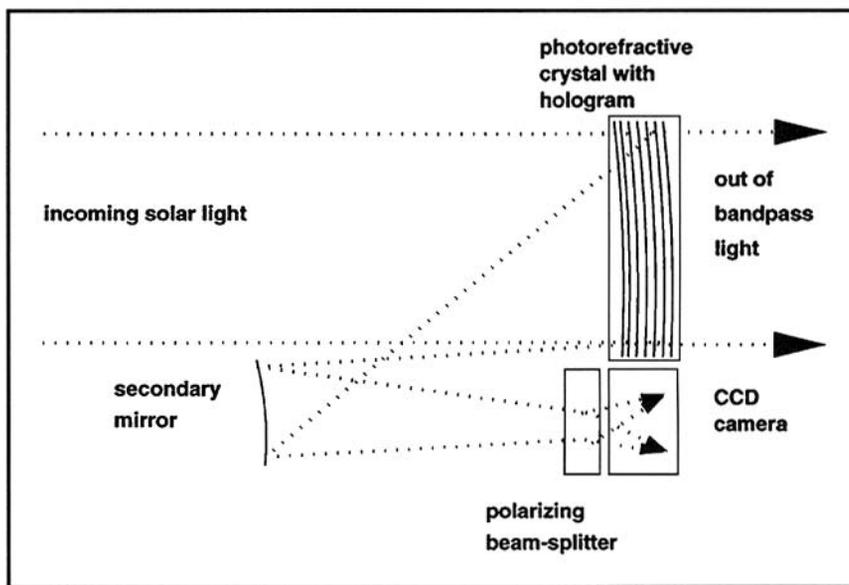


Figure 5. The optical arrangement of a miniature solar magnetograph.

STEREO

Planning is underway on the Solar Terrestrial Relations Observatory (STEREO), which will give researchers a new perspective on the CMEs surging directly toward Earth.⁸ STEREO will consist of two or more spacecraft in Earth's orbit around the Sun, but they will lead or follow Earth by hundreds of millions of kilometers. These spacecraft will carry coronagraphs and compact telescopes operating in the extreme ultraviolet or x-ray band. By imaging the events aimed at Earth, they will provide up to four days' warning of a storm.

Besides coronagraphs, the STEREO spacecraft may carry telescopes called tomographic imaging polarimeters (TIPs).⁹ These are highly baffled fisheye telescopes that can detect the light scattered by the electrons of CMEs, even as they approach and sweep past Earth. Several TIPs viewing the same CME from various positions will provide data for three dimensional reconstructions. With them, researchers hope to be able to learn why CMEs twist and turn in the solar wind and have either a strong or weak impact on Earth. Building the telescope's baffles is a heady technical challenge, however, because the baffles and optics must reduce instrumentally scattered sunlight by about 13 orders of magnitude.

The STEREO telescopes will be the first in deep space to make high-resolution images of the Sun. There will be tremendous pressure to reduce the weight and size of telescopes and detectors. They may finally weigh only a few hundred grams. For example, current designs for the TIP include rotating polarizers, but for STEREO, we are planning to bond a polarizing beamsplitter to a detector array and bring the weight of the polarizer down to a few grams. Figure 5 shows how a microlens array, a beamsplitting wafer of birefringent material, and a detector array can be combined to make a tiny polarization imager. The detector itself can be highly

Glossary

Atomic particle radiation: Electrons and protons that have been accelerated to energies above 10 million electron volts.

Magnetograph: An instrument for mapping solar surface magnetic fields.

Magnetosphere: Teardrop-shaped region in which Earth's magnetic fields prevail against the solar wind.

Photorefractive crystal: Natural or man-made crystal that changes index of refraction when exposed to light.

Solar flare: A sudden brightening, usually with an associated eruption of material.

Solar wind: Relatively steady, 400 km/sec, flow of solar gases in interplanetary space.

integrated with the processing electronics, producing a combined weight of 200 g.¹⁰

The polarization of the light reflected from a CME is measured because the apparent polarization depends on the angle made by the Sun-to-CME vector and the CME-to-detector vector. This angle is related to the distance of the CME from the detector. In general, nearer clouds along a given sight line will be polarized less than more distant clouds. Because the electron clouds are so faint and thin, only by measuring their polarization can one separate near ones from far ones and determine if they are on a vector aimed at Earth.

Ideally, STEREO will consist of four spacecraft. Calculations¹¹ show that tomography of CMEs will be much more accurate with four views than with three, but economics may limit the number of STEREO spacecraft to fewer than four.

There are several ideal positions in the solar system for STEREO spacecraft. Any position well-separated from Earth will represent a tremendous advance. A spacecraft that leads Earth in its orbit could pinpoint the sources of energetic atomic particles headed for Earth. This is because particles follow the garden-hose

spiral of the solar wind, and their source on the Sun is often on the backside (as described by a viewer on Earth).

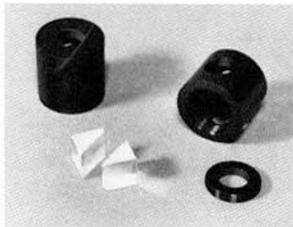
A spacecraft following Earth in its orbit by 60–90° could see solar active regions on their way to the front side, well before Earth-bound telescopes can see them. Since the most harmful eruptions come from active regions with large sunspots and strong magnetic fields, it is important to know of approaching regions as much in advance as possible.

Crunching the data

As imaging becomes the favored method of monitoring space disturbances, the need for data compression increases. The telemetry rates for deep-space missions are dramatically lower than for Earth-orbiting spacecraft. Hence, an important area of technology development for solar researchers is image restoration, analysis, and compression of spectral data. Custom camera systems are being developed that are software configurable,¹² so that they can provide high resolution during quiet episodes and, during stormy periods, high image rates at low resolution.

CLASSICAL OPTICS

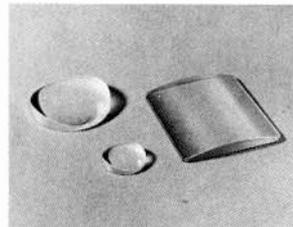
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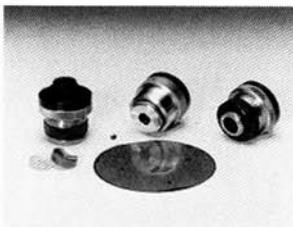
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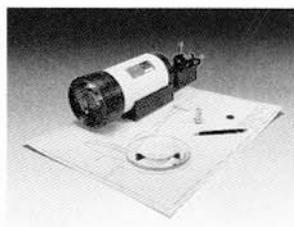
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Another approach to the problem is resolution enhancement through dynamic imaging, *i.e.*, combining images made before and after sub-pixel displacements of a steerable mirror.¹³ These efforts have already led to improvements in the effective spatial resolution of the coronal images obtained by the SOHO mission. This technique opens up possibilities for obtaining occasional images at very high resolution, whenever competing demands on telemetry systems allow more bandwidth to the imaging instruments.

Solar Probe

Perhaps the most challenging mission to the Sun currently under consideration is the Solar Probe.¹⁴ Some researchers argue that the only way to truly understand how the solar wind is accelerated is to fly a spacecraft very near the Sun. Solar Probe would be launched toward Jupiter and take advantage of the giant planet's gravity to shed most of its orbital angular momentum. The Jupiter encounter slows Probe to almost a dead stop in inertial space—so it literally falls into the Sun. The Probe would zoom to the Sun in only 26 months. A brief burn from a small rocket on board will direct it over the north pole at only three solar radii from the Sun's surface. The heat load will be incredible: 3,000 times the load at Earth's surface. The greatest challenge of the Solar Probe mission may be to devise a heat shield for the instruments or to find a power supply with sufficient dynamic range, but the radiation and image sensors will be difficult as well. Graphite-cyanate composites are being studied for the critical optical structures.¹⁵ They have excellent dimensional stability in high temperature gradients and greater heat resistance than conventional graphite-epoxy materials.

Solar Probe presents other formidable challenges such as how to build a solar telescope that is many times smaller and lighter (200 g) than existing ones. One approach uses a photorefractive crystal as both focusing element and spectral filter.^{16, 17} Figure 5 shows the concept for a compact, magnetograph to measure solar surface magnetic fields remotely from the Probe. A magnetograph must isolate bands in the solar spectrum that are only 0.1 Å wide. Traditional magnetographs achieve this with grating spectrographs or filters that pass only one band at a time. Hence, they require a large aperture.

A photorefractive crystal, perhaps specially doped lithium niobate, could have many holographic gratings written into it so that many 0.1-Å bands from magnetically affected regions of the solar spectrum could be brought to a focus simultaneously on a detector. The effective collection area of the telescope would be increased by the number of spectral regions imaged.

The principle of the photorefractive filter has been demonstrated in the laboratory, but possible interference effects between gratings and the stability of holograms under high photon and particle fluxes has to be established.

Summary

I have tried to touch on some of the problems that motivate solar research and new technologies for exploring the Sun. As we enter a new century of space exploration and space exploitation, we will be relying on the research results and routine "weather channel" images from a new generation of innovative telescopes.

Acknowledgments

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