Chapter 22

# Sunbeam

## In This Chapter

- X-rays penetrate
- Rockets go high enough to record x-rays
- Yohkoh mapped the x-ray Sun for 10 years
- Other spacecraft also map high-energy solar radiation
- X-ray telescopes can piggyback on Earth-viewing spacecraft

As the space age advanced, glimpses of the Sun from rockets gave way to spacecraft that provided longer views. During the 1990s, a Japanese spacecraft named Yohkoh provided continuous, high-quality x-ray images that allowed scientists to study violent processes on the Sun.

# Imaging X-Rays

When Wilhelm Roentgen discovered x-rays in the 1890s, he soon produced a photograph of his wife's hand, with her wedding ring showing prominently around the finger bone. Images like that dazzled the world. Such x-ray images show both the desirability of using x-rays and some of the problems with them.

*Roentgen's wife's hand, including her ring, taken in 1895. This image is often called the first x-ray photo.*

*(Radiology Centennial, Inc.)*

The x-radiation is produced by high-energy processes. Your doctor or dentist's office has such devices in order to produce the x-rays used for diagnosis. But we are not x-raying the Sun by putting radiation through it. Rather, we are examining directly the x-rays that are generated by high-energy and high-temperature processes on the Sun.

**Solar Scribblings**

Why are they called x-rays? Because they were mysterious. Not long after Roentgen found them, many other types of rays were reported. One, in particular, was called N-rays. Dozens of other scientists confirmed the detection. But the existence of N-rays seemed implausible on other grounds. In 1904, a scientist investigating the N-rays secretly removed the prism that was reported to be necessary to produce them; the scientist who initially reported the N-rays claimed to see their effects anyway. His self-deception was thus exposed. The episode drove the original scientist mad.

The hotter a gas is, the farther to shorter wavelengths its radiation peaks. That is, there is some wavelength at which a gas gives off more energy than at either longer or shorter wavelengths. The position of this peak wavelength shifts to shorter wavelengths as the gas gets hotter. For the solar photosphere, with a temperature of about 6,000 kelvins, the peak is in the yellow-green part of the visible spectrum. For the solar corona, with a temperature of perhaps 3,000,000 kelvins, the temperature is 500 times higher, so the peak of the wavelength is 500 times shorter. That puts the peak in the x-ray region of the spectrum.

You can't merely put an ordinary lens in a telescope to focus x-rays, since the lens would just get x-rayed. Scientists use several techniques to make images of celestial objects with x-rays. One way is to use a set of holes or channels, much like the honeycomb of metal that you often see on commercial fluorescent light fixtures. Only the x-rays going straight ahead through the small channels are recorded, and their position on film or electronic sensors can be noted. Especially for the longer-wavelength part of the x-ray spectrum, thin coats of metal can be deposited on glass lenses. The x-rays bounce back and forth between the coats of metal, and the property of light known as interference allows images to be made.

The property of grazing incidence can be used to focus all x-rays, including the shortest. If you throw a rock straight down on a body of water, it may just make a plop and not bounce off. But if you throw a rock across the same body of water at a low angle, it may skip across at a low, glancing angle. The same property is used to make high-resolution x-ray telescopes. NASA's giant Chandra X-ray Observatory, the x-ray equivalent to the Hubble Space Telescope, was launched in 1999 with a nested set of cylindrical mirrors, each of which focuses x-rays at glancing angles. Because the mirrors are intercepting the incoming x-rays almost edge on, they present a very small surface for collecting the radiation, which is why the mirrors are bent around in cylinders with several of them nested together—just to provide more area.

**The Solar Scoop**

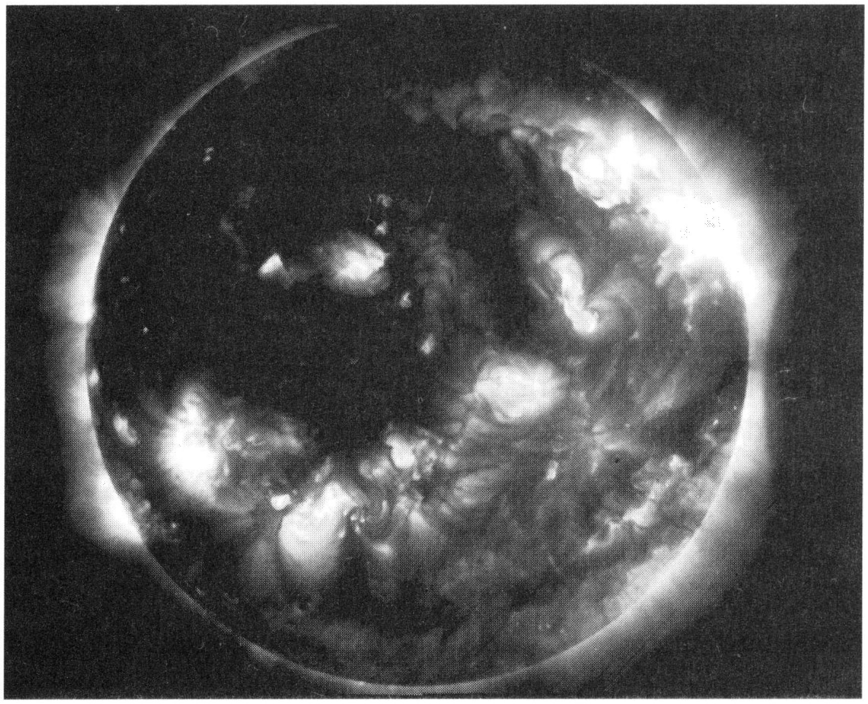
The Chandra X-ray Observatory uses grazing incidence to make very high-resolution images of celestial objects. Its resolution reaches half an arc second. But the Sun is too bright a source to point directly at; the intense sunlight would burn out the detectors.

# Solar Rockets

Though spacecraft are best for long-term monitoring of the Sun, there is still a substantial advantage to using rockets. For one thing, once the spacecraft are aloft, we usually can't modify them. Their sensitivities can change, for example, fooling scientists on the ground. Furthermore, sounding rockets are cheaper than orbiting spacecraft.

It is thus useful to launch, from time to time, a rocket that carries well-calibrated instruments. In the five-minute period or so that it is above the atmosphere, it can make observations that overlap the satellite observations. When the rocket is recovered back on Earth, its instruments can be checked to verify that their sensitivities haven't changed. Then the rocket results can be compared with the spacecraft results to provide accurate calibration of the latter.

Furthermore, the rockets can carry instruments or filters that aren't on the existing spacecraft. For example, a rocket timed to coincide with the 2001 eclipse made observations in 16-times-ionized nickel, a type of radiation released at higher temperatures than could be measured from the spacecraft then aloft. A rocket launched in 2002, whose results were reported at a 2003 meeting of the American Astronomical Society, also provided unique data.



*The x-ray corona in as much detail as has ever been seen, imaged with a rocket in soft x-rays using face-on rather than grazing incidence techniques. The flight took place on the same day that a total solar eclipse was visible from Earth. See Chapter 9 for another rocket x-ray solar image.*

*(Leon Golub, Smithsonian Astrophysical Observatory)*

**Fun Sun Facts**

An eclipse shadow moves across the surface of the Earth at speeds that get as low as 1,000 or 2,000 km/hr. But orbiting spacecraft usually move at 18,000 miles per hour. So the mismatch between a spacecraft and an eclipse is worse than the mismatch between the ground and an eclipse. Even if the spacecraft passed through the umbra, it would do so in seconds. So the purpose of eclipse rockets is to view the Sun within hours of the eclipse so that the measurements can be compared with those made during totality. Indeed, x-ray observations from the rockets show the corona across the face of the Sun, which would be hidden if the rockets were themselves inside the zone of totality.

# Yohkoh's Decade

After decades of progress in solar x-ray astronomy, it became possible to have an x-ray telescope in orbit in space for an extended period. The Japanese space agency, the Institute of Space and Astronautical Science (ISAS), stepped up to the plate to launch a satellite to study high-energy phenomena on the Sun, largely through x-ray images.

## Launching Yohkoh

Earlier, in 1981, ISAS had launched a smaller mission to study solar flares. It was called Hinotori, which means "fire-bird." After its success, Japanese scientists and engineers designed a larger mission, called then Solar-A, to observe flares and other activity on the Sun with higher resolution. It would resolve better not only spatial details of flares, but also their energy ranges. Furthermore, it would be sensitive enough to record the quiescent regions between the active regions.

Solar-A was successfully launched on August 30, 1991, from the Japanese space facility. It was then named Yohkoh, which means "sunbeam." It is in a circular orbit, circling Earth every 96 minutes.

## Using Yohkoh

Many of the images displayed with discussions of Yohkoh were taken with the Soft X-ray Telescope, the United States' contribution to the mission. The telescope was built at the Lockheed Palo Alto Lab in collaboration with the National Astronomical Observatory of Japan, and was later controlled by scientists at Montana State University in Bozeman. It used a grazing-incidence telescope and a series of thin metallic filters to observe different wavelength bands between 3 and 12 angstroms. (Those wavelengths correspond to photons of energies between 4 and 1 kilo-electron volts [keV], the unit often used to measure energies.) The Soft X-ray Telescope had a resolution of 4 arc seconds, inferior to ground-based resolution in the visible part of the spectrum, but still very useful. It could take images every two seconds. Also important, it could record brightness over a very wide range, greater than a factor of 100,000. Thus, it could sense both faint objects and bright ones on the face of the Sun.

Yohkoh also carried a Hard X-ray Telescope. By "hard," scientists mean that the x-rays are more energetic, which means that they have shorter wavelengths. The Hard X-ray Telescope imaged flares with wavelengths from 5 to 20 times shorter than the Soft X-ray Telescope—that is, from 0.6 to 0.2 angstroms. The images had resolutions of 7 arc seconds. The telescope could take images as often as every half second, to follow the eruption and growth of a solar flare.

Yohkoh also carried devices to measure x-ray and gamma-ray spectra of flares

## The Death of Yohkoh

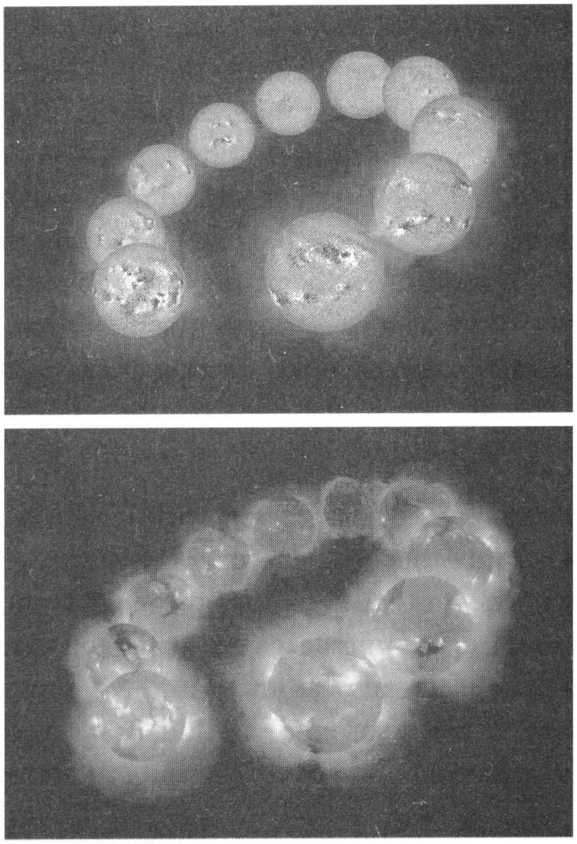
Yohkoh worked very well for about a decade, and a tenth-anniversary celebration was planned. Shortly before the date, Yohkoh passed into the eclipse path of what on the ground was the annular eclipse of December 10, 2002, observed in Costa Rica. For some reason, the sensors on Yohkoh went wild as Yokhoh passed into the eclipse path, and the spacecraft started spinning. In spite of hopes that it might be tamed, as Solar Maximum Mission had been 18 years earlier by astronauts and as the Solar and Heliospheric Observatory had been more recently using ground controls, Yohkoh never came back.

## Yohkoh Science

The continuous stream of Yohkoh images allowed the overall structure of the Sun to be observed as it changed over the 11-year solar-activity cycle. The individual images show that the hottest regions of the corona, as revealed by their brighter x-ray emission, correspond to the regions of the strongest magnetic field in the solar photosphere. The magnetic field was mapped by ground-based observatories.

At the maximum of the sunspot cycle, in 1991 and in 2001–2002, not only are the magnetic field areas and sunspot areas larger than at all other times, but also the bright regions of the corona seen in x-rays are the most extended. The magnetic field lines that come out of the Sun broaden a bit by the time they reach coronal altitudes, so the x-ray bright regions are slightly larger in extent than the sunspots visible in the photosphere. At the minimum of the sunspot cycle, the overall x-ray corona is perhaps 100 times fainter and has many fewer magnetic regions showing. The bright regions that fade are replaced by only smaller, fainter regions.

After sunspot minimum, the orientation of the magnetic field changes. In particular, the positive polarity of the magnetic field leads the negative polarity in the northern hemisphere during one cycle, as the figure shows. Leading means that it goes first in the direction that the Sun is rotating. At the same time, the reverse is true in the southern hemisphere, with the positive polarity trailing the negative polarity. After sunspot minimum, these pairings are flipped. The positive polarity then trails in the northern hemisphere and leads in the southern hemisphere. Only after another full 11-year cycle do the polarities flip again and the Sun returns to its earlier magnetic configuration. For this reason, the true sunspot cycle is 22 years long, not merely the 11 years that you would superficially think, because you were looking only at the sunspot numbers rather than at the underlying magnetic field.



*The variation of the solar magnetic field (top) and x-ray images from Yohkoh (bottom) over a whole solar activity cycle, in series of images taken approximately a year apart.*

*(X-ray images: LMSAL, Montana State U., NASA, NAOJ, U. Tokyo, and ISAS; magnetic images: NSO/AURA/NSF)*

# Exploring Small

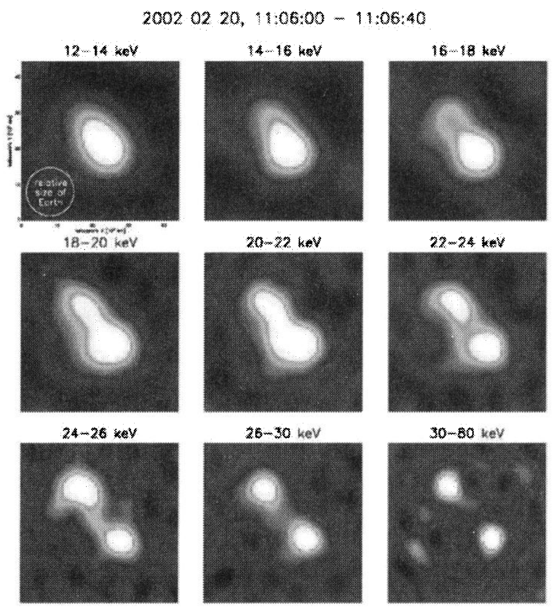
NASA has several series of spacecraft in different price ranges. One of its Small Explorers is devoted to studying solar flares. Originally named the High Energy Solar Spectroscopic Imager, the spacecraft was renamed about a month after its launch in 2002 to honor the memory of the late gamma-ray NASA scientist Reuven Ramaty. It is in a low Earth orbit inclined 38°.

The Ramaty High Energy Solar Spectroscopic Imager (RHESSI) makes images with unprecedentedly high spatial and high time resolution, in order to study the explosive phases of flares and other solar phenomena. To make those images, it uses a metal grid; computers on the ground calculate the image that is built up as the spacecraft rotates. In hard x-rays, those at wavelengths less than 0.3 (20 keV in energy), its images have a resolution better than 4 arc seconds. Those images should improve to about 2 arc seconds as more information about the details of the spacecraft's operation are assimilated. RHESSI also measures the spectrum of those individual elements by recording the brightness in discrete energy bands. Furthermore, it takes spectra of gamma-ray spectral-line emission in flares.

RHESSI has observed thousands of flares in hard x-rays and dozens in gamma rays. The largest of these flares gives off more energy than a million megatons of TNT. The researchers are looking, in particular, for the locations of the emission of the most energetic x-rays and gamma rays, in order to find the sources of the huge amounts of energy. Scientists are sure that the energy is locked up in the magnetic field, but there is no agreement on the details of the mechanism for storing the energy or for triggering its explosive release. Spectra show that x-rays are generated from electrons given so much energy that they move at speeds greater than half that of light. These electrons stream downward along the magnetic field, starting at the peak of the coronal loop. The spectra also show that the gas is heated to tens of millions of degrees during the flare's peak.

Project scientists have localized powerful flares with RHESSI. By aligning these observations with those from other spacecraft, they have zeroed in on the flare mechanisms. The images have shown that the x-rays given off from the footpoints—the places where the flare loops descend that we see at higher levels are anchored in the photosphere—are caused by electrons slamming into the dense gas lower in the corona and in the chromosphere. It was a surprise that the x-rays were seen coming from the footpoints before other spacecraft showed brightening in their ultraviolet observations.

RHESSI's sensitivity is enough to find that tiny flares, lasting only a few minutes each, happen all the time. So x-rays are being generated at a low level fairly continuously—and not only in the few spectacular flares that previously were all that could be studied.




*The solar flare of February 20, 2002, observed in different energy bands from the Reuven Ramaty High Energy Solar Spectroscopic Imager.*

*(NASA's Goddard Space Flight Center and UC Berkeley)*

# Go GOES

X-ray telescopes provide sensitive monitoring of solar activity. So it is useful to observe the Sun in x-rays constantly and to keep track of what is going on. But we don't always have to launch special spacecraft to do so. After all, we have many spacecraft aloft for other reasons. In particular, satellites in Earth orbit get their energy from solar panels. These panels always face the Sun, so why not just mount telescopes on them to study the Sun? This is now being done.

The Geostationary Operational Environmental Satellite (GOES) is a series of Earth-viewing satellites sponsored by the U.S. National Oceanic and Atmospheric Administration (NOAA). Satellites in this series send back pictures of the Earth's weather, among other things. As of the GOES-M, which was launched in 2001, an x-ray telescope was mounted on the solar panels.

GOES-M's x-ray telescope, which went into routine use in 2003, is a grazing-incidence model, in order to give high resolution that isn't available with other ways of focusing x-rays. It can send down x-ray images every minute, using several bands of x-ray wavelengths between 6 Å and 60 Å. NOAA scientists intend to use the image to study the relation of the Sun and Earth, and the images are immediately available on the web.

## The Least You Need to Know

- X-ray telescopes take special forms to focus at such high energies.
- X-ray observations can be made from rockets aloft.
- The Yohkoh satellite made 10 years of x-ray solar images.
- A current spacecraft is observing x-rays and gamma rays from flares.
- Weather satellites can piggy-back x-ray solar imagers.