Solar Outbursts

From radio waves to gamma rays: The fingerprints of solar flares

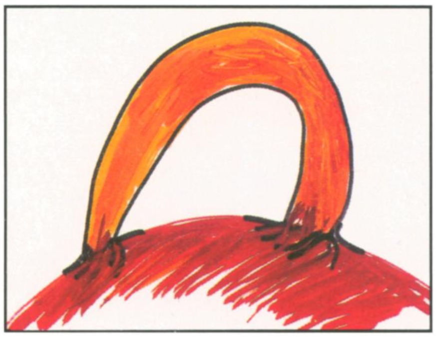
By RON COWEN

Think of the sun's magnetic fields as the ultimate in rubber-band power.

Anchored in the sun's visible surface, these fields loop outward, sometimes arching thousands of kilometers into the upper reaches of the solar atmosphere. And when stretched or twisted, they build up vast amounts of energy.

Stresses result when a buried magnetic field suddenly pokes through the sun's visible surface, or when the sun's rotations jerk one magnetic anchor of a loop into a new position, or when one loop bumps into an oppositely directed, neighboring loop.

Whatever the cause, when a magnetic field is strained beyond its limit, it snaps. And then all hell breaks loose. Releasing a fireball of energy into the sun's upper atmosphere, broken magnetic fields trigger one of the most puzzling — and riveting — of solar phenomena: a flare.



Crannell

Drawing of magnetic loop showing its two footpoints, or anchors, in the lower reaches of the solar atmosphere. Not all magnetic fields on the sun form closed loops; some have just one anchor, with the open end of the loop extending far into space, where it may join with an interplanetary field.

This sketchy picture of the creation of a solar flare remains open to debate. But the spectrum of radiation released during and after a flare — running the gamut from radio waves to high-energy gamma rays — has recently come into sharper focus. Several new detectors on Earth and in space that record the duration, location, and intensity of each type of solar radiation offer new clues to the nature of these fiery outbursts.

"We are beginning to get a clearer picture of solar flares and their radiation," says Mukul R. Kundu, a solar radioastronomer at the University of Maryland in College Park.

In a flare, the burst of energy released by magnetic fields accelerates ionized gas (charged particles) in the sun's upper atmosphere, or corona. It may also lift charged particles from the sun's dense lower atmosphere, or chromosphere. These particles fill the series of closely spaced magnetic loops that form an arcade high in the corona. Electrons spiral tightly around each loop, emitting a barrage of radio waves and prompting nearby gas to radiate low-energy X-rays. Some of the accelerated particles slam into the chromosphere, striking atoms and triggering a burst of highly energetic X-rays and gamma rays, as well as visible light — the hallmark of a flare. Other charged particles get trapped inside the magnetic loops, where they rattle back and forth, leaking out over a period of hours. Like the energetic electrons before them, these exiting particles collide with atoms in the chromosphere, creating a faint glow of gamma rays that can last for hours after the main flare peters out.

At a June meeting of the American Astronomical Society in Columbus, Ohio, Kundu and other astronomers presented new findings on the myriad types of radiation produced by flares.

In one study, Kundu and his colleagues focused on millimeter-wave radio emissions. Electrons accelerated to several million electron-volts of energy emit these radio waves in the corona as they spiral around strong magnetic fields. These same electrons also appear to generate gamma rays when they strike dense matter during a flare.

Until recently, notes Kundu, detectors lacked the sensitivity and spatial resolution needed to detect millimeter-wave radiation from typical solar flares. But using a group of radio telescopes known as the Berkeley-Illinois-Maryland Millimeter Array (BIMA) in Hat Creek, Calif., the researchers managed to subtract the background of radio waves emitted continually by the sun and to record just the radiation resulting from flares. Homing in on emissions from regions of the solar atmosphere as small as 750 kilometers across, they found several unique features in the radiation pattern.

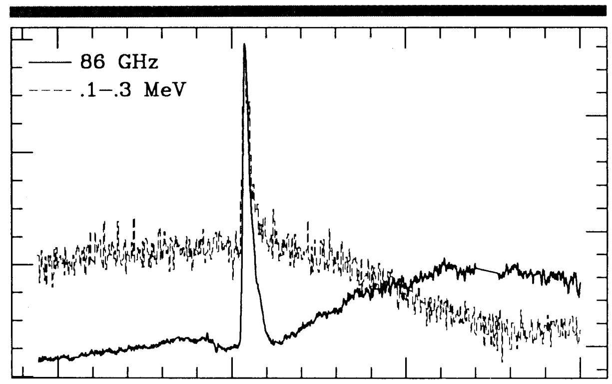
The team observed millimeter-wave radiation from both large and small flares, indicating that even small-scale eruptions have the power to accelerate a large number of electrons to high energies. Although the bulk of the emission lasted only a few seconds, some of the radiation persisted, peaking and then diminishing in intensity over several minutes.

Kundu says this finding supports other observations that even a small flare can spread to neighboring regions of the solar atmosphere. He proposes that some of the electrons initially accelerated by the flare give up their energy to a dense, less energetic collection of charged particles in adjacent magnetic loops. As the less energetic particles heat up, they too emit radio waves. This is the radiation that lags behind the initial millimeter-wave burst and lasts longer.

Using the Very Large Array radio telescope near Socorro, N.M., Kundu and several collaborators also studied microwave emissions — radio waves associated with lower-energy electrons. They found that the microwave emissions peaked a few seconds before the millimeter-wave radiation.

One explanation, says Kundu, is that the coronal magnetic fields deliver their energy in a one-two punch. First, they accelerate electrons (and other charged particles) to energies ranging from 50,000 to 100,000 electron-volts. Then, any leftover magnetic energy accelerates other electrons to higher energies, up to several million electron-volts, accounting for the short delay in millimeter-wave emissions.

Examining emissions from a solar flare that erupted last year, Kundu and his colleagues compared the timing of radio waves recorded by BIMA with that of gamma rays detected by the Earth-orbiting Compton Gamma Ray Observatory (GRO) (SN: 6/22/91, p.388). They found that the intensity of the radio waves and gammas peaked and diminished in sync, providing new evidence that high-energy electrons generate both types of radiation. At the tops of magnetic loops, the electrons emit radio waves. In the dense, lower atmosphere near the bottoms of the loops, electrons rain down upon atoms, triggering the release of gamma rays, Kundu explains.



Intensity of microwaves (solid line) and gamma rays (dotted line) emitted during a solar flare that erupted on June 13, 1991, shows that both types of radiation peaked at the same time. This suggests that microwave emission observed during a flare may reveal the pattern of gamma ray emissions.

Kundu et al.

The researchers were equally intrigued to discover that millimeter-wave radiation mimics the emission pattern of gamma rays. This means that efforts to construct the first millimeter-wave image of a solar flare should also provide new information about gamma ray emissions from the sun, Kundu says. He and his coworkers expect to create such an image from their BIMA data in the next few months. In an unrelated experiment, Carol Jo Crannell of NASA's Goddard Space Flight Center in Greenbelt, Md., and her colleagues hope to begin imaging flares in the light of hard X-rays and gamma rays using a seven-foot-long balloon-borne telescope that they hope to fly for two weeks this fall.

Both electrons and protons may contribute to the gamma ray afterglow detected by GRO, Kundu says. At a press conference in Washington, D.C., last month, other researchers reported that GRO had detected gamma rays from the sun for more than five hours after a solar flare erupted on June 11, 1991, and for 90 minutes after the onset of another flare four days later (SN: 7/25/92, p.54).

Investigators have suggested that the afterglow stems exclusively from protons. Some of these charged particles, accelerated by the energy unleashed at the outset of a flare, apparently get trapped inside magnetic field loops in the corona. Electrons, many scientists reason, would quickly radiate their energy and could not survive for long in such a trap.

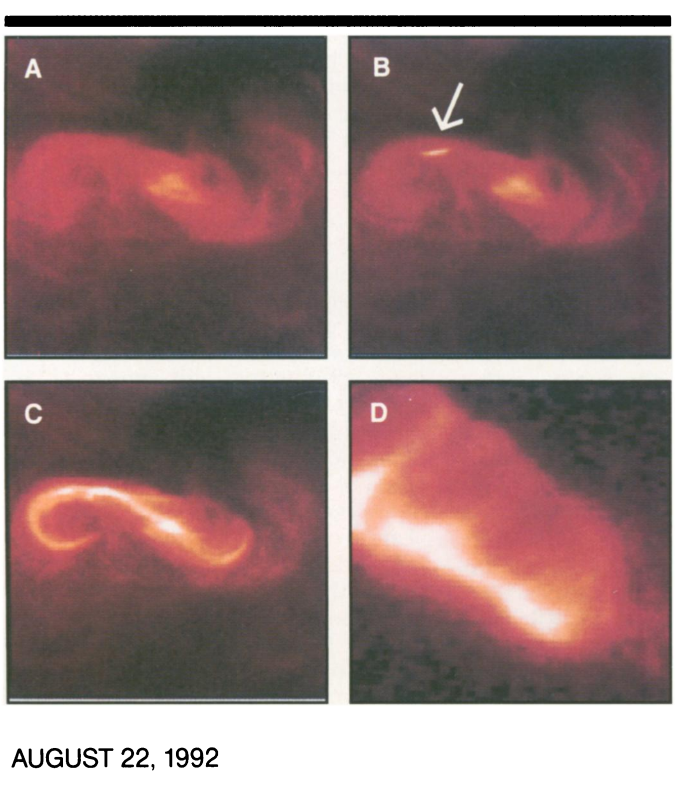
Kundu agrees that high-speed electrons will lose their energy much faster than protons of comparable energy. But last year, he notes, Japanese astronomers found that some millimeter-wave emissions persist for two to three hours after the onset of a flare.

Their observation, made with a radio telescope at the Nombeyama Solar Radio Observatory in Nagano, Japan, suggests that energetic electrons can survive as long as a few hours inside a magnetic trap, Kundu says. During that time, protons *and* electrons that leak out of the trap can rain down upon atoms in the chromosphere and spark the emission of gamma rays, he says. Reuven Ramaty of NASA's Goddard Space Flight Center and Natalie Mandzhavidze of the University of Maryland cite such a possibility in their analysis of gamma ray afterglow, reported in an upcoming ASTROPHYSICAL JOURNAL. They also suggest that the fields somehow enlarge their volume or twist their shape in order to form better traps.

Yet another orbiting observatory has begun monitoring solar flares. The satellite Yohkoh, which means sunbeam in Japanese, has been busy viewing solar X-rays since its launch last August (SN: 6/20/92, p.404). Although short-term balloon flights and some satellites have previously observed X-ray activity on the sun, this Japanese-built craft has charted flares in more detail than any other instrument, says Yohkoh investigator Keith T. Strong of the Lockheed Palo Alto (Calif.) Research Laboratory.

Constructing one of the more dramatic sets of images to emerge from flare studies, Strong and his colleagues joined forces with Lockheed researchers who study visible-light emissions at the Swedish Solar Observatory in Spain's Canary Islands. The visible light observed by the scientists comes from hydrogen gas in the sun's chromosphere. Combining Yohkoh images of the higher-altitude, X-ray component of a flare with its visible-light counterpart, researchers accomplished a unique feat. Using telescopes that could locate magnetic features with unprecedented accuracy, they succeeded in simultaneously imaging the bottoms of magnetic loops, which lie anchored in the dense lower atmosphere, and their very tops, high in the hot corona.

Brian R. Dennis, a solar astronomer at NASA's Goddard Space Flight Center, reports that data collected last year by Yohkoh's high- and low-energy X-ray telescopes have now confirmed a flare feature first predicted in 1969 by Goddard scientist Werner M. Neupert. According



Strong *et al.*/Lockheed/Univ. of Tokyo/Nat'l Astronomical Obs.

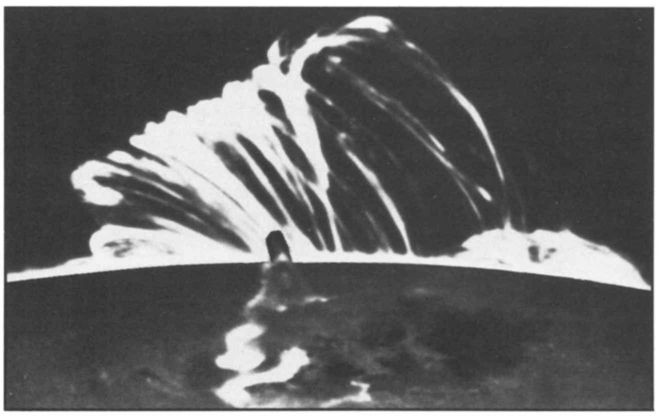
This sequence of X-ray images, taken with the Yohkoh satellite, shows the evolution of a flare that erupted on May 8, 1992. Photo A: Before the flare erupted, hot gases in one region of the corona traced out an S-pattern of highly magnetic fields, apparently stretched to near the breaking point. Photo B: Some 90 minutes later, a small flare erupted (see arrow). Photo C: The flare reached its soft X-ray peak after about 30 minutes, lighting up a larger region of the corona. Photo D: After the flare died down, the magnetic fields appeared to have adopted a less stretched configuration.

to Neupert's theory, just as the initial burst of "hard," or energetic, X-rays accompanying a flare reaches its peak intensity, a gentler, longer-lasting glow of "soft," or less energetic, X-rays begins. Neupert had proposed that as electrons accelerate to high energies, emitting radio waves and colliding with atoms to create the hard X-rays, they also heat the ionized gas inside neighboring magnetic loops. At a temperature of about 20,000 kelvins, the heated gas would emit soft X-rays. And since the ionized gas would cool slowly, that emission would persist for an extended time.

While some flares do indeed exhibit an extended cascade of soft X-rays on the heels of the intense, hard X-ray burst, others seem to lack the soft X-ray component. Until recently, however, results were inconclusive because orbiting telescopes couldn't take enough X-ray snapshots to see the effect clearly. By taking both hard and soft X-ray images of flares every few seconds and by mapping regions as small as 1,400 kilometers across, Yohkoh has now provided researchers with the information they need to verify the scenario. Dennis notes that images from the soft X-ray telescope show that the source of the low-energy X-rays shifts location by some 21,000 kilometers during the flare – another indication that these eruptions spread out over large regions of the solar atmosphere.

Images taken with Yohkoh's hard X-ray telescope seem to confirm another, more basic tenet of flare activity, says Takeo Kosugi of Japan's National Astronomical Observatory in Tokyo. These images show that twin, high-intensity X-ray bursts appear simultaneously at the two footpoints of a magnetic loop – the anchor points where magnetic fields leave the hot corona and enter the dense chromosphere. The pictures indicate that the charged particles that collide with atoms to create these X-rays must have originated at the top of a magnetic loop high in the corona. In this low-density region, where charged particles encounter relatively few atoms, electrons and protons can travel unimpeded down a long loop, brilliantly illuminating each footpoint, as the Yohkoh pictures illustrate.

Had the particles received an energetic kick much lower in the atmosphere, says Strong, they would have collided with many more atoms and the Yohkoh images would have looked very different. While some of the charged particles would have brightly illuminated one of the footpoints with hard X-ray emissions, collisions would have prevented most of them from ever reaching the second footpoint. Thus, this second anchor would have appeared much fainter in the light of high-energy X-rays.



Bogdan Rompolt, Wroclaw University Observatory

The bottom half of this composite image, taken in visible light, shows sunspot activity at the low-energy X-ray peak of a flare. Four hours later, the glow from gases in the corona (top half) traces out an arcade of magnetic loops that traps charged particles. Particles that slowly leak out of this "magnetic bottle" and collide with atoms near the solar surface may account for the gamma ray afterglow recorded hours after this flare erupted on June 15, 1991.

While researchers may understand how flares generate certain types of radiation, they have no clear understanding of the detailed magnetic interactions that trigger these eruptions in the first place.

No detector yet has the resolution to image individual magnetic fields, the most obvious method for studying the evolution of these arching structures, says Strong. But by looking at the solar disk overall, scientists may glean clues to the structure of flares and magnetic fields. "It's interesting that we need to go to a smaller scale to understand what goes on in flares, but we also need to look at the larger scale to understand what's driving the flare," he says. Such large-scale phenomena include the movement of sunspots and the constant upwelling, or convection, of hot gas from deep within the sun.

Over the past few months, Strong notes, the sun has quieted down and scientists have trained Yohkoh on the overall structure of the corona, rather than on flares. The satellite's X-ray eyes have mapped gradual changes in the corona, recording the waxing and waning of such features as coronal holes, the source of high-speed solar wind streams; active regions where sunspots and future flare activity may occur; and run-of-the-mill quiescent spots in the corona. Eventually, these studies may yield a more complete picture of how and when magnetic fields store and release energy.

Charles A. Lindsey of the Solar Physics Research Corp. in Tucson, Ariz., has a different idea for trying to understand the changing pattern of magnetic fields on the sun. Building upon a recent discovery that magnetic fields absorb sound waves, he and his co-workers suggest that by "listening in" on the sun, astronomers may be able to detect buried fields months before they emerge on the visible solar surface and trigger new activity.

Researchers can't place an acoustic detector on the sun, Lindsey notes. But they can monitor sound waves indirectly by measuring fluctuations in the intensity of a familiar wavelength of visible light. This wavelength is absorbed by calcium ions in the sun's lower atmosphere. Over the past 10 to 15 years, scientists have found that some of the intensity fluctuations – those that occur about every five minutes – correlate with the intensity of sound waves on the solar surface. These waves, in turn, probably result from the turbulent motions of gases inside the sun.

Analyzing data on calcium absorption collected by a camera mounted in the Antarctic during the austral summer of 1987, Lindsey and his co-workers, including Douglas Braun of the University of Hawaii in Honolulu, found faint, finger-like shadows in the acoustic maps they constructed. The shadows seemed to connect regions of high surface magnetic activity, even though those regions were some 500,000 kilometers apart. Lindsey's group attributes the shadows to sound-wave absorption by submerged magnetic fields that appear to stretch across the solar equator and connect bands of magnetic activity in the sun's northern and southern hemispheres. The researchers report these findings in the June 20 ASTROPHYSICAL JOURNAL.

Lindsey told SCIENCE NEWS that a month or two after dark areas on an acoustic map indicated the presence of a submerged field inside one area of the sun, a significant increase in magnetic activity did appear on the surface. "We believe we are seeing submerged magnetic activity that will appear on the surface one or two months later," he says.

His group now hopes to develop three-dimensional images – acoustic holograms – of the interior magnetic structures. That project is likely to take several years of complex computer modeling. But the work, he says, may one day offer a peek at the churning, changing pattern of magnetic field activity – months before sudden twists or turns prompt these rubber-band-like powerhouses to unleash their energy. □