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Solar Flares, Proton Showers, and the Space Shuttle

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Flares, which are sudden brightenings on the solar surface, affect our environment in many ways. Some effects are harmless, even beautiful, but others may be costly and have important consequences for the space shuttle program. The 10 April 1981 flare heated the earth's upper atmosphere and increased the drag on the space shuttle Columbia during its maiden flight of 12 to 14 April. The flare caused a great red aurora on the night of 12 April and an ionospheric storm that interfered with police communications, but not with shuttle communications. In fact, the flare posed no serious problems for the Columbia. If the shuttle mission had included an extravehicular activity in a polar orbit, however, the mission probably would have been put off to avoid exposing astronauts John Young and Robert Crippen to a proton shower. Solar flare protons with an energy of more than 10 million electron volts can penetrate the aluminum layers of most space suits (*1*).

Solar flares were the subject of an intensive study in the international Solar Maximum Year, which ended in February 1981. The National Science Foundation and the National Aeronautics and Space Administration (NASA) led U.S. support of the effort. In all, more than 400 solar physicists from 17 countries worked together to document and model every stage in the buildup, release, and propagation of flare energy. Before discussing the models and the first results of the Solar Maximum Year, I will review the most important consequence of flares for space missions—the hazard from a proton shower.

Summary. The space shuttle era will focus renewed attention on the hazards of the space environment to human habitation. The chief unpredictable hazard for astronauts is energetic proton radiation from solar flares. In some orbits, there is no reasonable level of shielding material that will protect shuttle occupants from potentially lethal doses of radiation. The effects of a solar flare that occurred during the first flight of the Columbia are discussed and current flare research reviewed. The emphasis is on progress made during the recent international Solar Maximum Year toward understanding the origins of proton showers.

Radiation Hazard

An ambitious shuttle program will be confronted with threats posed by various sorts of space radiation (*2*). Charged particles trapped in the Van Allen belts, for example, may cause gradual damage to materials on missions of long duration and may damage large structures in space through static discharges. But the greatest challenge will be to ensure that astronauts and others who work in space will not be exposed to lethal or disabling solar radiation. During the Apollo program the radiation hazard was qualitatively the same, and NASA created a Solar Proton Alert Network to evaluate and warn of proton shower risks. Studies of the radiation hazards made in the 1960's for the Apollo program are still the most comprehensive available (*2*). No way has yet been found to avoid proton showers, but so far astronauts have been at risk for only a few days each year. The risk from proton showers was small compared to other risks that the astronauts faced. In the shuttle era, however, the relative importance of the hazard from proton showers will require reconsideration since there may be people in space almost continuously.

NASA hopes to have a permanent manned space station in orbit by 1990, and this and other projects may rely on extensive extravehicular activity. One study (*3*) estimated that NASA could save about $3 billion by using extravehicular activity to deploy, maintain, and repair satellites.

The nearly complete shuttle launch facility at Vandenberg Air Force Base will be used primarily to launch missions into polar orbits, where the radiation hazard is substantially higher than that in the low-inclination orbits used by shuttles launched from the Kennedy Space Center.

The risks to those who work in space for 3 months or more are potentially great. Careers in space may not be feasible if a worker can absorb a lifetime's radiation allowance in a few missions. Both long- and short-term exposure levels will have to be considered since background cosmic radiation, particles trapped in the earth's magnetic fields, and six to ten proton-producing flares a year will deliver a continuous dose of radiation. The long-term effects of such radiation will not be discussed here. Radiological studies do indicate, however, that the effects of exposure are cumulative (*4*).

In this article, I will describe the risks posed by major solar flares, which start suddenly and can deliver in a few hours a disabling or even lethal dose of radiation. The largest doses can be two to three times the level lethal to a man. A lethal dose could be delivered over a period of several days, but at peak flux rates, a 1-hour exposure would cause nausea and possibly vomiting (*5*, *6*).

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Table 1. Predicted radiation dose in shielded work space for 1-year exposure.

Orbit		Dose (rads) from		
Altitude	Inclination	Trapped and cosmic rays	Solar flares*	Total
400 km	30°	32		32
400 km	90°	28	80	108
Geosynchronous	Geosynchronous	300	250	550

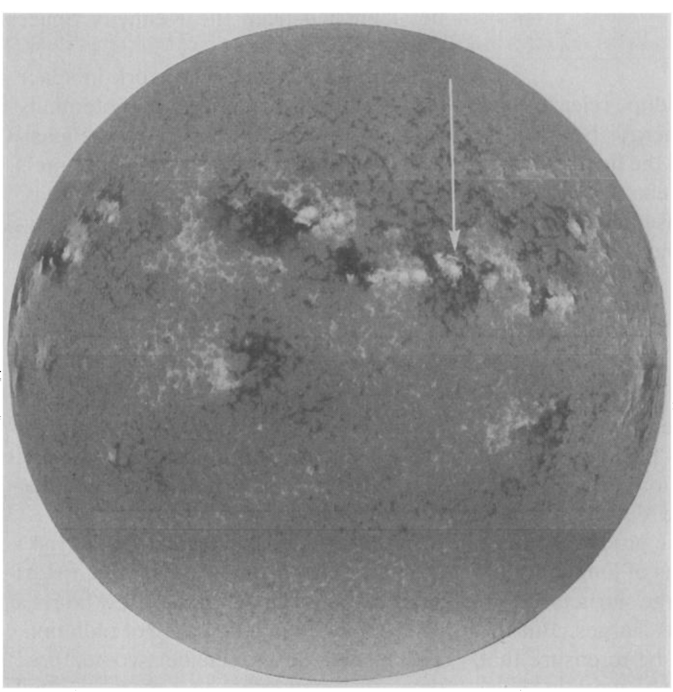
*For a 99 percent confidence level at maximum, that is, one chance in 100 that a 1-year exposure at solar maximum will exceed these doses.

Table 2. Suggested proton exposure limits in rads for Apollo crew members.

Constraint	Bone marrow	Skin	Ocular lens	Testes
Average daily rate	0.1	0.3	0.15	0.05
30 days	12	40	20	6
Yearly	40	110	55	20
Career	200	600	300	100

Space radiation risks for short and long missions currently can be evaluated only in a statistical way. Stassinopoulos and King (*7*) at the Goddard Space Flight Center used modified Poisson statistics to estimate radiation doses at geosynchronous altitude (35,000 kilometers) during a 90-day mission. They found that if a major proton shower occurred, astronauts in a shielded working area would receive a dose of 155 rads. Hospital x-rays, by comparison, give less than 0.01 rad. An astronaut outside the shielded working area during a major proton shower could receive about 1000 rads. Over 90 days the total dose due to ordinary proton showers would be about 10 rads. But this estimate is strongly dependent on statistical assumptions, and it does not account for trapped radiation and cosmic rays. Another estimate (Table 1), prepared at the Marshall Space Flight Center (*8*), of exposure for 1 year to all penetrating radiation inside a shielded work space, when compared to the suggested exposure limits for Apollo astronauts (Table 2), indicates the level of risk for lengthy manned space activities in geosynchronous and polar orbits is unacceptable because of flare protons. Standards in industry are much more stringent than those proposed for the astronauts (*9*).

It may be possible to design around hazards from trapped radiation, but better short-term forecasting of solar flares will be required to avoid aborting missions unnecessarily or exposing astronauts to a hazardous stream of protons. Insight into the physical processes that cause proton showers will be essential because short-term forecasting is reaching the limit that can be achieved with purely statistical methods (*10*). At present, flare forecasts are based on statistical correlations between flares and sunspots, solar radio emission level, earlier flares, and other solar parameters. Many of the characteristics of solar activity used in forecasts are measured only once each day. More frequent measurements usually reveal no changes above the background noise level, which is determined by atmospheric conditions at the solar observatories. Thus, there is a fundamental limit to the accuracy of the forecasts. To understand this, suppose that the average rate of flares that disturb the space environment is 0.25 per day. Even if this average rate is known to a high degree of precision, Poisson statistics tell us that a forecast of "flare" will be wrong 80 percent of the time.



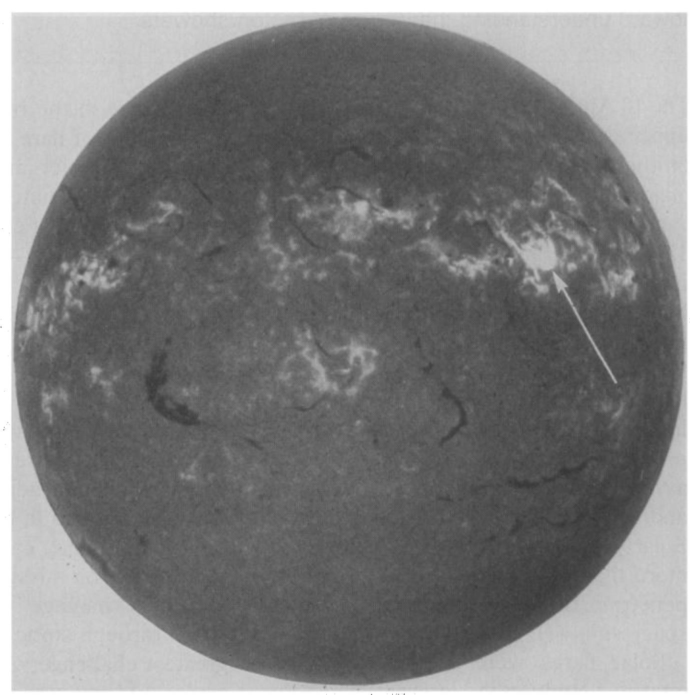


Fig. 1 (left). Magnetogram of solar surface fields on 9 April 1981, showing positive (upward pointed) fields in white and negative (downward pointed) fields in black. The arrow marks the complex fields that appeared from beneath the visible surface 24 hours before the 10 April proton flare. [Photograph courtesy of J. Harvey, Kitt Peak National Observatory] Fig. 2 (right). The sun at the peak of the 10 April flare. The flare (arrow) covered 1.8×10^9 km^2. [Photograph courtesy of G. Heckman, National Oceanic and Atmospheric Administration, Space Environmental Laboratory]

A Flare Chronology

The physical processes operating in flares are not well understood, although the effects are well documented. To trace these phenomena in detail, I will describe the flare phenomena of 10 to 13 April 1981 and their effects on the earth. When first observed on 2 April, the sunspot group that would give rise to the flare of 10 April was a single spot. Spots themselves have no effect on our planet, but their magnetic fields twist and stretch until some instability releases pent-up energy and causes a flare. There was little change in the spot group until 7 April when a moderate flare occurred. On 8 April, 16 new, small spots burst into the region, and five more flares occurred. On 9 April, the number of sunspots grew to 29, and there were eight more small flares. Still, there was no reason to suspect that a major flare was only 48 hours away.

On 9 April, the sunspot group was classified as a complex magnetic region. The magnetic fields in the group formed an unusual and complicated mosaic of upward and downward pointed fields (Fig. 1). A chain of tiny positive and negative spots encircled the large positive spot that had been observed since 2 April. Only about 10 percent of all spot groups attain such complexity, and almost all large flares come from such complex groups.

By the morning of 10 April the number of spots had increased by only one, but flare activity increased dramatically. Seven subflares preceded the giant flare, which engulfed the sunspot group at 1645 Greenwich mean time, 5 hours after the originally scheduled launch of the Columbia and 43 hours before the actual launch. In only a few minutes, electrons and protons began streaming outward toward the earth and inward to denser layers of the solar atmosphere. Intense emission appeared throughout the electromagnetic spectrum (*11*).

The flare lasted for 3½ hours. At its peak, it covered an area of 2×10^9 square kilometers on the solar disk (Fig. 2). The flare released over 10^{25} joules or about 10^{19} kilowatt-hours of energy or about 400,000 times the total yearly energy consumption of the United States. This amount of energy could easily have been stored in the magnetic fields of the sunspot group even though the sunspots showed no changes as a result of the flare. Gradually, solar physicists have been able to rule out many other invisible storehouses once proposed as flare energy sources. The invisible energy stored in twisted magnetic fields is the only plausible energy source for flares (*12*).

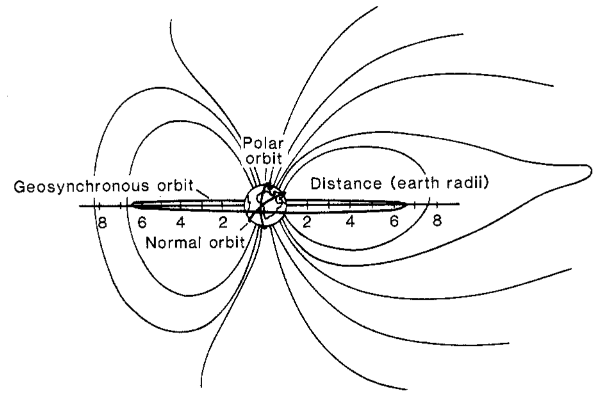


Fig. 3. Sketch showing the most frequently used satellite orbits and the magnetic fields that deflect protons. Geosynchronous orbits are fully exposed to proton showers. A satellite in polar orbit is exposed about 30 percent of the time. Satellites in 30° orbits are well protected from solar protons.

In the first 10 minutes after flare onset on 10 April a shock wave started out through the corona. After 58 hours the shock hit the earth's magnetosphere and triggered a magnetic storm. The actual decrease in the horizontal component of the magnetic field at the earth's surface was barely 1 percent of the quiet time value, but the effect was sufficient to accelerate billions of electrons in the magnetosphere and produce a power outage in Canada. The 12 April magnetic storm, which began only 15 hours after the launch of the Columbia, was the largest of the current sunspot cycle (*13*).

The earth's upper atmosphere was swamped by electrons that rushed in from the storm. The electrons raised the temperature at 260 km over Boulder, Colorado, from a normal temperature of 1200 K to about 2200 K. This temperature increase, the greatest recorded by the National Oceanic and Atmospheric Administration (NOAA) in 15 years of measurements, swiftly changed the orbit of the Columbia. The heating expanded the atmosphere and dragged the shuttle (and other satellites) down into lower orbits 60 percent faster than expected (*14*). The early demise of Skylab in 1978 was due to such an unexpected increase in atmospheric drag. In general the present sunspot cycle is much more active than predicted, and our upper atmosphere is much more extended because of this. An extended atmosphere exerts more drag on all satellites and pulls them into lower orbits. The drag effect increases exponentially with density since, by Kepler's law of planetary motion, a satellite moves faster in a lower orbit, thereby losing more energy to atmospheric drag; it drops into still denser layers of the atmosphere, moves faster still, suffers more drag, and quickly burns up. On the Columbia, Young and Crippen simply fired the retrorockets early to correct for the overshoot on reentry. But even a little extra drag on satellites built to operate for years could be costly if they are lost prematurely or required to carry expensive on-board maneuvering capability.

Solar Protons

The most energetic protons from the 10 April flare reached the earth's atmosphere an hour after flare onset, and they would have posed a potentially lethal threat to astronauts on an extravehicular activity in a polar or geosynchronous orbit (Fig. 3). The peak flux of protons with energies of 50 to 500 megaelectron volts had passed by the Columbia's launch time, but 10-MeV protons continued to stream into the magnetosphere until early on 14 April, the day of reentry (*13*). Young and Crippen were never in any danger, however, because the Columbia flew in a low-latitude, low-altitude orbit, where the earth's magnetic field provides adequate shielding against everything except very energetic cosmic rays. The average proton flux on 10 April was about 300 particles per square centimeter per second. The event was an ordinary proton shower. About ten such showers can be expected each year near the sunspot cycle maximum. The highest fluxes recorded in the past quarter-century were more than 100 times higher than those on 10 April (*7*), and they occurred in anomalously large events that happen perhaps one to six times each solar cycle during the rise and fall from solar maximum. The next solar maximum will occur in 1990.

How are solar protons accelerated to high energies? Direct production of a beam of 10-MeV protons requires a drop in electric potential of 10 million volts. It is unlikely that such a potential could be established on the sun since the solar atmosphere is composed of highly ionized gas, or plasma, that conducts electricity with higher efficiency than pure copper. Electrons in the plasma will move almost instantaneously to short-circuit any electrical differences that might accelerate protons.

The search for another way to explain how these solar cosmic rays are accelerated began shortly after announcement of their discovery in 1946 (*15*), but solar flare data were intermittent before the International Geophysical Year in 1958. Then, a worldwide network of observatories was established to monitor the sun 24 hours a day. At about the same time the riometer, which measures the relative ionospheric opacity to cosmic radio noise, was invented. Solar protons with energies of 10 to 100 MeV spiral into the polar cap and increase the ionization there. The added ionization absorbs cosmic radio waves and can be directly related to the proton flux (*16, 17*). Before development of the riometer, only proton showers at energies above 500 MeV could be recorded. Satellite-borne detectors have since lowered the threshold for detection of flare protons to about 0.5 MeV.

From the start it was clear that only some large flares cause proton showers. Also, proton showers generally miss the earth when emitted from a flare on the sun's eastern hemisphere. The preference for the western hemisphere (as seen from the earth) was explained in 1962 as a result of channeling by the solar wind (*18*). Parker (*19*) had proposed the existence of a solar wind to explain why ionized comet tails point away from the sun. The solar wind stretches the sun's magnetic fields in an Archimedes' spiral out to well beyond the earth's orbit, and protons released at the base of a spiral follow it outward (Fig. 4). Flares that occur in the sun's western hemisphere are well connected to the earth, and the most energetic protons can reach the earth in as little as 20 minutes (*20*).

Even after the channeling effects of the solar wind were accounted for, solar physicists were not able to distinguish proton-producing flares from other flares. They tried to find clues in pictures of the optical emissions (Fig. 2), but the photographs show plasma with an average particle energy of only 1 electron volt. Solar magnetograms and pictures of sunspots (Fig. 1) do show what the surface magnetic fields are doing and, since Fermi (*21*) had shown that protons could be accelerated in colliding magnetic fields, it seemed reasonable to search for colliding magnetic fields in flares.

Magnetic Fields and Neutral Sheets

Giovanelli (*22*) showed that flare occurrence is statistically associated with complex and changing sunspots. Martres and her colleagues (*23*) and Severny (*24*) established that flares start near growing or decaying sunspots. I found that the changing magnetic features were actually fresh magnetic fields emerging from below the solar surface. Flares frequently start precisely at these emerging fields. On this basis, Heyvaerts, Priest, and I proposed (*25*) that the magnetic energy was released principally as heat and in beams of particles accelerated in collisions between the old and new fields.

Our model invoked two earlier ideas about magnetic fields in flares. One, proposed by Sweet (*26*) held that energy can be drained out of the solar magnetic fields where two oppositely directed fields come into contact (Fig. 5). Along what Sweet termed a "neutral sheet," strong electric currents will flow and rapidly heat the plasma. The mechanism, however, could not explain the rapidity of the heating. Then Petschek (*27*) showed that magnetic fields, if pushed together with sufficient speed, would generate shocks, which would greatly increase the rate of energy conversion. Petschek called this process "magnetic field annihilation." Solar physicists had realized that magnetic fields were the only plausible energy source for flares, and now Petschek's theory could explain how magnetic energy could be converted to intense heat in 1 minute, or less, as observed in flares. Additionally, the neutral sheets might provide escape routes for accelerated protons into interplanetary space.

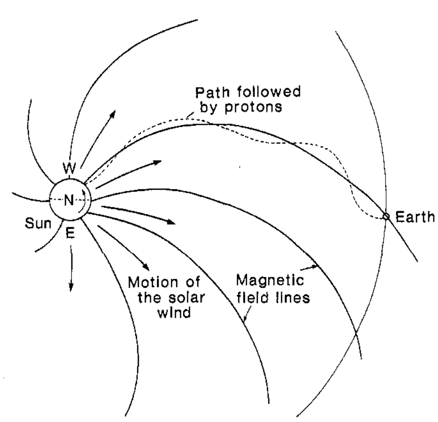


Fig. 4. Solar wind, magnetic field lines, and a proton trajectory. The solar wind pulls magnetic fields radially away from the sun at about 400 km/sec, but the solar rotation of 2 km/sec twists the fields into a gradual spiral. Protons released at the base of magnetic fields 20° to 80° west of the central meridian are said to be well connected because they do not have far to drift across the spiral pattern to reach the earth.

Skylab. In 1973, pictures of flares obtained by American Science and Engineering and the Naval Research Laboratory strongly challenged the emerging flux model. These x-ray and ultraviolet pictures from Skylab showed nothing that looked like the current sheets that the model requires. Every flare consisted of a single bright loop (Fig. 6) or, sometimes, an arcade of bright loops. Proponents of current sheets argued that the sheets were too thin to photograph and that the loops simply showed trapped hot plasma. Hot plasma and accelerated particles should quickly exit from any current sheet. Another possible explanation was that the Skylab telescopes showed only the aftermath of the energy conversion process (*12*, p. 212; *28*). Then Spicer (*29*) proposed a model based on experience in laboratories with tokamaks in which toroidal fields confine hot plasma for fusion research. Such fields are subject to internal instabilities that are well known to laboratory researchers, and Spicer suggested that solar magnetic fields are annihilated not at neutral sheets, but within the elemental magnetic loops themselves, as in tokamaks.

Spicer's model seemed to describe the Skylab flare pictures. The model required no more than what was seen—no hard-to-detect colliding fields or impossible-to-detect neutral lines—but it did not provide a route by which protons could enter interplanetary space.

Solar Maximum Year: First Results

Until recently, efforts to understand flares and proton showers were hampered by a lack of comprehensive observations of all the phenomena involved. During the Solar Maximum Year (*30*) solar physicists assembled the ground-based and satellite instruments needed to record everything, from the first tentative increase in x-rays to the proton shower and shock wave in space. NASA launched the International Sun-Earth Explorer to monitor the particle fluxes and solar wind near the earth as well as a $100-million observatory, called the Solar Maximum Mission. Most instruments for the Solar Maximum Mission (*31*) were specially designed to probe flare energy release processes with x-ray and ultraviolet images and spectra. There was also a coronagraph to photograph the large magnetic loops (Fig. 7) that burst into interplanetary space during some flares. Thousands of flares were recorded before the Solar Maximum Mission lost solar pointing control; the experiments on the Sun-Earth Explorer and a cluster of solar telescopes aboard Air Force satellite P78-1 are still functioning. Although enough flares have now been studied to provide new insights, the conclusions drawn must be treated with caution because flares vary widely. Nevertheless, the results seem to point the way to understanding the origins of proton showers.

The hot flare loops discovered with the Skylab telescopes are about 6000 km wide and about 30,000 km long—just within the resolving power of the hard x-ray imaging spectrometer (HXIS) on the Solar Maximum Mission (*29*). Using the HXIS, Hoyng and other Solar Maximum Mission investigators compared maps of electron emission with magnetic field maps and optical images (*32*). The optical images (Fig. 2) obtained by "flare patrol" telescopes operated by NOAA and the U.S. Air Force are especially useful for clarifying magnetic field structure because they show features as small as 500 km in diameter. We were able to show that a flare on 21 May 1980 started with two bursts of electrons in adjacent magnetic loops. The electrons, identified by characteristic x-ray bremsstrahlung as they penetrated the chromosphere, must have been accelerated somewhere in the magnetic loops or at a neutral sheet between loops.

Within a minute of the x-ray bursts, the loops filled with 70×10^6 K plasma. Spectra from another Solar Maximum Mission experiment, the x-ray polychromator, showed that the plasma boiled up from the chromosphere. As it cooled, it began to emit ultraviolet and optical radiation that illuminated the magnetic loops only a few minutes after the first release of energy.

From the 21 May observations electron beams were located unambiguously in the heart of a flare. Zirin (*33*) and others had guessed that electron beams caused the intense optical emission at the bases of flare loops, but without HXIS images, it was not possible to distinguish between the action of electron beams and conduction from the flare plasma. The HXIS observations clearly separated the x-ray emission of the electron beams from the equally intense x-ray emission of the 70×10^6 K plasma.

Besides clarifying the acceleration and heating sequence in flare loops, the 21

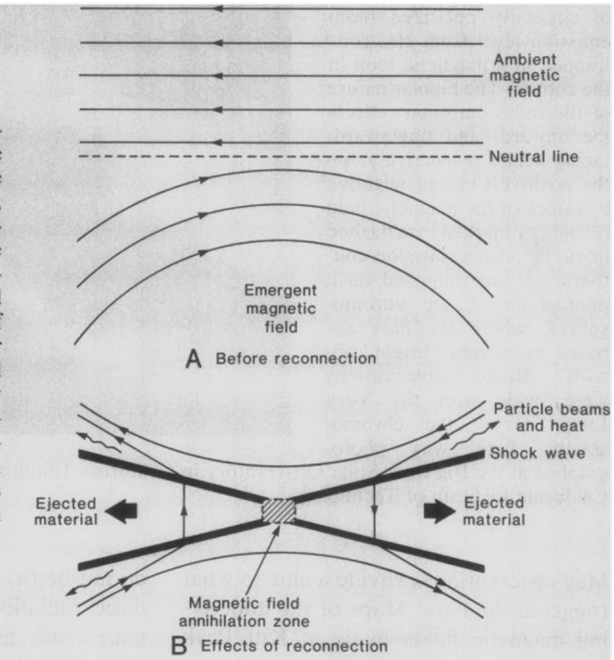


Fig. 5. Magnetic field annihilation. Magnetic fields in the solar plasma behave like stretched rubber bands (A), and the effect of field annihilation is like that of cutting the bands and retying them to produce shorter but more relaxed segments (B). Annihilation of magnetic fields may occur where oppositely directed fields are pushed together by outside forces, such as convection or a shock wave. Energy is released in heat, shocks, and energetic particles near the neutral sheet between the fields.

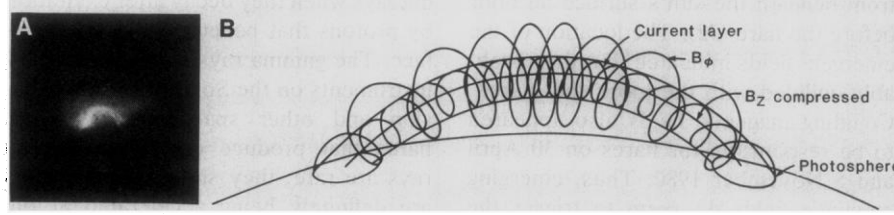


Fig. 6. The 10^7 K plasma kernel in flares, as shown by x-ray telescopes aboard the Skylab. (A) In most cases the plasma resembles half a torus. (B) Plasmas of similar temperature are confined in tokamaks by sheared magnetic fields. The laboratory experience of plasma physicists suggests a number of ways to convert the energy of the confining fields into the intense heat of the plasma. The loop's length in (A) is 1/13th of the sun's diameter.

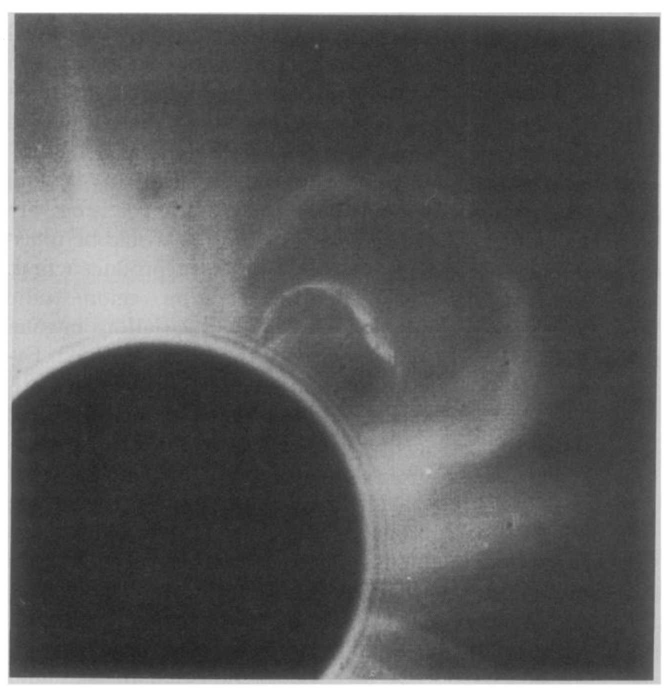


Fig. 7. Solar Maximum Mission coronagraph image showing expanding loop on 14 April 1980 pushing material out of the solar atmosphere at 700 km/sec. The diameter of the loop is approximately the same as that of the sun. Most of the energy in a large solar flare is carried away by such coronal mass ejection. In front of the leading edge of the bright material is a bow shock, detectable only by the radio emission it excites. This photograph was made in filtered sunlight reflected from electrons trapped in the loop. The sun is blocked by a disk. [Photograph courtesy of L. House, National Center for Atmospheric Research]

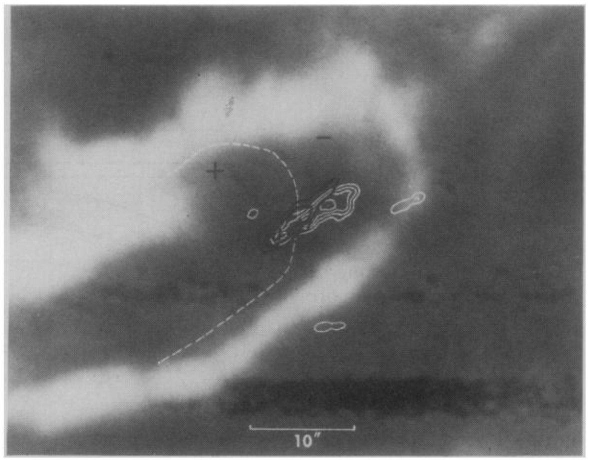


Fig. 8. Contours (solid lines) of circularly polarized radio emission level from electrons trapped in a magnetic loop in the corona. The bipolar nature of the radio emission reflects the upward- and downward-facing fields, respectively, on the positive (+) and negative (−) sides of the magnetic field boundary (marked by a dashed line). The radio emission contours are superimposed on a photograph of the chromosphere, where the flare appears as several bright ribbons. Radio observations were made with the Very Large Array; the chromospheric flare was photographed at the Big Bear Solar Observatory in California. [Photograph courtesy of G. Hurford, California Institute of Technology]

May observations provide a clue to what triggered the flare. Maps of the underlying magnetic fields made at Kitt Peak National Observatory showed that tiny strands of magnetic field were emerging from beneath the sun's surface an hour before the flare (*32*). The location of the emergent fields indicated that they probably collided with the loops that flared. Colliding magnetic fields also appeared to be responsible for flares on 30 April and 5 November 1980. Thus, emerging magnetic fields do seem to trigger the process that converts magnetic energy into heat and beams of accelerated particles.

Investigators using the Very Large Array of the National Radio Astronomy Observatory found more evidence for electron beams in the loops (*34*, *35*). During a half-dozen flares, they mapped emission from electrons with energies of 100 to 500 kiloelectron volts. Such electrons spiral in magnetic loops and emit synchrotron radiation, whose polarization and location reveal the nature of the electron population and outline magnetic fields. The radio wave–emitting loops pictured by the Very Large Array stretch over the magnetic fields in exactly the same way as do the x-ray–emitting loops shown by the HXIS, except that at radio wavelengths the electron beams emit mostly at the loop tops (Fig. 8). Some of the radio pictures also seem to show colliding loops (*35*).

Proton Acceleration

Electrons in flares stream away from points, perhaps neutral sheets where magnetic fields collide. All the theoretical mechanisms for particle energization indicate that protons should be accelerated whenever electrons are, but protons do not betray their presence in flares by direct radiation; we must infer their presence from nuclear reaction products. The affected nuclei, mostly of hydrogen, carbon, nitrogen, and oxygen, emit gamma rays when they decay after excitation by protons that penetrate the solar surface. The gamma rays were detected by instruments on the Solar Maximum Mission and other spacecraft. Although flares that produce detectable gamma rays are rare, they show when protons are definitely being accelerated at the sun.

In a large flare on 7 June 1980 several successive gamma-ray bursts followed similar x-ray bursts by less than 2 seconds (Fig. 9) (*36*). The inescapable conclusion is that the proton beam was being created in the same small (by solar standards) loop as the electron beam. If the size of the loop had been more than about 10^5 km, the fluctuations observed in the gamma rays would have been washed out by the spread in flight time of the protons. The fastest protons would arrive first and excite some nuclei; slower protons would arrive up to several seconds later and excite nuclei too, but the gamma rays emitted would be indistinguishable from those produced first. Thus, a big acceleration region would produce more gradual variations in gamma-ray emission than was observed. Evidently the acceleration region was small, and the protons were accelerated in the first seconds of the flare. Optical observations of the 7 June flare indicated that the proton acceleration region was probably a magnetic loop only a few thousand kilometers long (*37*). Yet the magnetic fields nearby were quite complex. Neutral sheets there could guide protons from the accelerator into space.

It was widely expected that gamma-ray emitting flares well connected to the earth would produce the strongest proton showers, and Pesses *et al.* (*38*) examined records of the International Sun-Earth Explorer for proton showers following three of the largest gamma-ray bursts. Two of the flares produced minor enhancements and one produced no shower at all. The study was then extended to all reported solar gamma-ray bursts, and still no correlation was found. If no correlation turns up in more detailed studies, then proton beams in gamma-ray flares are probably directed toward the sun's surface. Relatively few protons would escape in that case, and proton showers could not be predicted from gamma-ray flares.

Actually, the acceleration of a proton beam in a few seconds in a loop about the size of a sunspot came as a surprise. Most acceleration models are based on the Fermi mechanism and require 2 to 20 minutes to produce protons with energies greater than 10 MeV. The models divide proton flares into two stages. In the first stage, particles are accelerated to 100 keV in a turbulent neutral sheet. Whenever the impacts of the particles heat the chromosphere sufficiently, the dense plasma there expands explosively. A shock should streak through the corona at about 1500 km per second. Some of the protons from the first stage, then, might be accelerated as the shock sweeps through the overlying magnetic fields. The effect on particles would be the same as in Fermi's (*21*) original description of cosmic-ray acceleration in turbulent magnetic clouds; that is, protons already accelerated in the first stage could be accelerated to energies as high as 10^9 eV.

There were problems with the two-stage scenario even before the data from the Solar Maximum Mission showed that 10-MeV protons can be created in the first stage. Forecasts of proton showers based on the first-stage emissions are notably inaccurate. There is a poor correlation between first-stage emission level and proton shower intensity. Also, Mathews and Lanzerotti (*20*) had shown that the protons that struck the earth after one particularly large flare must have been accelerated into interplanetary space at the beginning of the flare. Delay times between 32 giant flares and their proton showers also indicate that proton acceleration occurs during flare onset (*39*). Further, Gloeckler *et al.* (*40*) showed that heavy nuclei in proton showers originate in the ambient solar atmosphere. If the nuclei are injected into the accelerator from the first-stage particle population, they would have ionization states characteristic of the hotter flare plasma. We needed a fast ion acceleration mechanism that does not require injection of hot flare particles. The accelerator would have to be triggered by some flare phenomenon but not fed by the flare particles themselves. It should be able to produce fast protons whether or not fast protons are produced in the flare itself.

Unnoticed by most solar physicists, Armstrong and his colleagues (*41*) were studying just such a mechanism in order to explain how ions are accelerated in shocks in interplanetary space (*42*). They succeeded in explaining the time profiles, anisotropies, and energy spectra of proton streams in shocks, and their acceleration model does not require first-stage injection from flares (*41*). Protons can be accelerated as they spiral in and out of the shock wherever it is almost parallel to the magnetic field. There is ample evidence for shocks and complex magnetic fields near large flares, and shocks and fields could meet at just the right angle to produce bursts of protons.

Pictures of the corona (Fig. 7) may show what the solar atmosphere looks like when a proton shower is developing. Munro, MacQueen, and their colleagues (*43*) found that every fast coronal eruption pushes a shock through the atmosphere ahead of it. Kahler, Hildner, and van Hollebeke (*44*) showed that every proton shower they studied was preceded by such a coronal mass ejection and shock wave. But sometimes there are shocks without coronal mass ejections. These seem to be blast waves triggered by the explosion of the chromosphere reacting under the intense heat generated by the flare. There is some evidence that the blast wave shocks decay quickly. Shocks driven by coronal mass ejections, on the other hand, can probably propagate to the earth (*45*). These shocks accelerate protons not only at the sun, but all the way along the route. The protons escape ahead of the shock face, and that is why they started arriving at earth an hour after the 10 April flare and kept coming until after the shock hit 58 hours later.

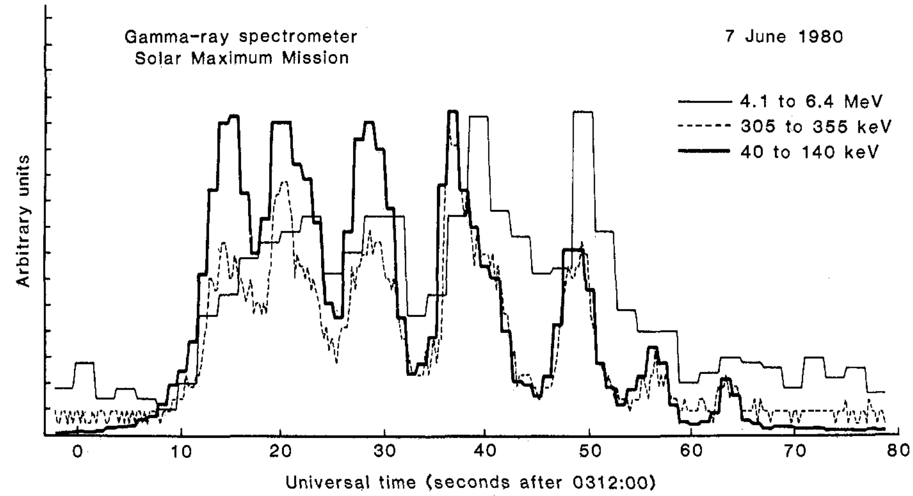


Fig. 9. X-rays and gamma rays from the flare of 7 June 1980. The bursts of x-rays lead the gamma rays by less than 2 seconds. The x-rays are emitted exclusively by electrons. The gamma rays can be excited only by protons. Both emissions result from beams penetrating the solar surface. The electrons and protons must have been accelerated at about the same time in a loop no more than 10^5 km long. Otherwise, time-of-flight differences between the electrons, whose velocity is near the speed of light, and the protons, at one-fourth the light speed, would have been more apparent. [Photograph courtesy of J. Ryan, University of New Hampshire]

Conclusions

It now appears that proton-producing flares signal their onset from the sun not by their x-ray spectra, nor by covering an unusually large surface area, nor by copious emission of gamma rays. Spacecraft observations indicate that protons are energized in shocks, many of which are driven by coronal mass ejections. The faster an ejection moves, the steeper is the shock and the more energetic the protons.

Proton showers require two stages of particle acceleration as well as a favorable magnetic field geometry. The first stage of acceleration usually involves electrons and, sometimes, protons in small magnetic loops near sunspots. Most particles do not escape from the sun (*46*) but lose all their energy in penetrating the solar surface. The heat generated there and in the flaring fields themselves causes the atmosphere near the flare to explode. Shock waves from the explosion as well as shocks from the mass ejections that accompany many flares probably accelerate protons where they strike the ambient magnetic fields of the corona at an angle of about 3° (*41*). The origins of coronal mass ejections and of pre-flare magnetic energy are still not known, however. Although solar physicists believe that they have discovered where particles are accelerated in flares, they cannot distinguish among the proposed mechanisms.

As a result of the new insights gained from the Solar Maximum Year programs, we can mount a new attack on the problems of forecasting proton showers, but many uncertainties will have to be resolved before forecasts turn into confident predictions. The acceleration process requires an angle of about 3° between shock face and magnetic field. The magnetic fields in the solar atmosphere are complicated. How can we predict whether a shock will hit them at the required angle?

A cluster of small telescopes could be launched to provide real-time pictures of the magnetic fields in the corona as well as of the solar surface. The fields show up as giant loops when photographed with an x-ray telescope. Such observations cannot be obtained from the ground. Coronal mass ejections passing through the loops should show where protons are being accelerated. Surface magnetic fields should be monitored from space where the measurements will not be degraded by weather conditions. Subtle shifts in the fields could be tracked by observations at 30-minute intervals and the measurements used to continuously correct magnetic field models. Magnetic field growth and collision courses could be recognized quickly. Even though the connection between emerging magnetic fields and flares is not clearly understood, flare forecasts based on known statistical associations could be freed from the fundamental precision limit imposed now by the diurnal pace of ground-based observations. Many other statistical parameters used in flare forecasting could be made more reliable by obtaining more data at shorter intervals.

From a practical point of view, improved solar data are needed to predict the weather that men will encounter as they work more regularly in space. Had the Columbia been launched on 10 April as scheduled and had the flight plan called for a polar orbit with an extravehicular activity, Young and Crippen would have encountered the proton shower. Polar missions are planned for the next decade, but without improved forecasting many may be short and costly.

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Suppression of Transcription Termination by Phage Lambda

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One of the most important advances in our understanding of gene regulation in prokaryotes came with the proposal of the "operon" concept by Jacob and Monod (*1*). This concept proposed that regulation of gene expression was achieved by controlling the frequency of initiation of transcription. However, while many genes are in fact controlled in this manner, it is becoming apparent that the transcription of very many other genes is regulated by an alternative mechanism—regulation by control of transcription termination (*2, 3*). Much insight into this process has been achieved by investigations into the mechanism of action of the phage lambda *N* gene product. This protein positively controls lambda development by preventing transcription termination (*4–8*).

Transcription Termination

Transcription initiated at a promoter must stop somewhere. By the operon theory, transcription of every gene of an operon is equal; termination of transcription is assumed to occur at the end of the operon. However, transcription termination can occur within an operon. Polar mutations are characterized by their capacity to inactivate both the cistron in which they are located and the cistrons promoter-distal to the site of the mutation (*9*). Polarity is caused by the action of transcription termination sites located within the operon which prevent transcription of distal genes (*2*). These intraoperonic terminator sites are normally nonfunctional but become active as a result of the polar mutation. Most mutations causing polarity are nonsense mutations that cause termination of translation; the lack of translation activates the transcription termination sites. Thus, terminator sites are not always active; their activity can be prevented or controlled.

Discovery of the "attenuator" structure (*3, 10*) proved that controlling transcription termination had biological significance as a means of gene regulation in wild-type operons. The attenuator is a transcription termination site typically located between the promoter and the

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