Why do stars emit x rays?

Careful study of our closest star, the Sun, suggests that bundles of twisted magnetic flux tubes extending from subsurface layers may account for the surprising prevalence of x rays from most rather ordinary stars.

Eugene N. Parker

The Sun was the first observed x-ray star. In 1948 rocket-borne instruments, carried out of the terrestrial atmosphere for only a few minutes at a time, detected solar x rays. Then in April 1960 instruments recorded the first x-ray photograph of the Sun.[1]

Some years later the orbiting High-Energy Astronomy Observatory 1 and the Astronomical Netherlands Satellite discovered the remarkable fact that the sky is filled with bright x-ray "stars." These "stars"—intrinsically many factors of ten brighter than the x-ray Sun—have turned out after careful investigation to be pathological objects. Often they are manifestations of the mutual interaction, through tidal forces and mass transfer, of close companion stars.

However, the next step in observing the x-ray universe was even more remarkable in some ways. With the rapid advance of technology, the orbiting HEAO-2 Einstein Observatory—launched in 1978—discovered that x-ray emission is part of the normal function of nearly every star, whether young or old, large or small, hot or cold.[2–4] The exceptional stars that do not emit x rays include cool giants, supergiants and white dwarfs. So x-ray emission, rather than being extraordinary, is ordinary. Or at least it would be if we understood the extraordinary physics of ordinary stars like the Sun.

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Extensive observations show that the most intense stellar x-ray emissions arise from transient flare activity. But there is a steady continuum of x-ray emissions, mostly thermal bremsstrahlung. This thermal radiation shows that each star has a tenuous outer atmosphere with a (kinetic) electron temperature of 10^6 K or higher. Why would a star emitting thermal blackbody radiation from a surface at 10^4 K (or less) possess an outer atmosphere several hundred times hotter? This is the central question I wish to address in this article.

Stellar x-ray diagnostics

Let us formulate the question in more quantitative terms. The x-ray emission is the principal means of energy loss from most stellar coronas. As a result we can take the x-ray luminosity as a measure of the energy input necessary to produce the corona. The effective (equivalent blackbody) temperature of the Sun is about 5800 K; this represents the solar "surface" temperature at an optical depth of unity. The x-ray luminosities of stars with surface temperatures below 6000 K are observed to lie in the range 10^{26}–10^{30} ergs/sec, while the occasional flare output may go up another factor of 100 for a brief period. The hotter stars are somewhat more luminous in x rays: O-supergiant stars, with surface temperatures of about 20 000 K, exhibit x-ray luminosities as large as 10^{34} ergs/sec, or a little more than twice the Sun's luminosity summed over all wavelengths—what we call the bolometric luminosity. The ratio of x-ray luminosity to total luminosity ranges from 10^{-5}–10^{-3} for the small, cool (3000 K) M-dwarfs to 10^{-7}–10^{-5} for some of the hotter, brighter stars. Thus the emission of x rays by a star is an indication that a small fraction of the star's total energy output is being diverted into production of a circumstellar halo or corona of million-degree gas. The precise value of that fraction depends, evidently, on the internal energy transport properties of the star.[5]

If we knew why the Sun is compelled to produce the patches of bright x-ray corona, we could use the x-ray emission as a diagnostic tool for probing the properties of other stars. At the present time, though, x-ray astronomy is working at the phenomenological level, noting interesting correlations between the x-ray luminosity and other measured—or inferred—properties of a particular star. These include mass, radius, composition, rotation rate, age and bolometric luminosity. Generally astronomers have been busy building a data base around the observed stellar x-ray emissions. Indeed, the Advanced X-Ray Astrophysics Facility that has been in the planning stage at NASA for some years will—one can only hope—one day probe considerably farther into space. The addition of precise x-ray spectroscopy will help determine the gross physical conditions in the corona of an x-ray-emitting star.

However, we must turn to the Sun both to see the resolved structure of the

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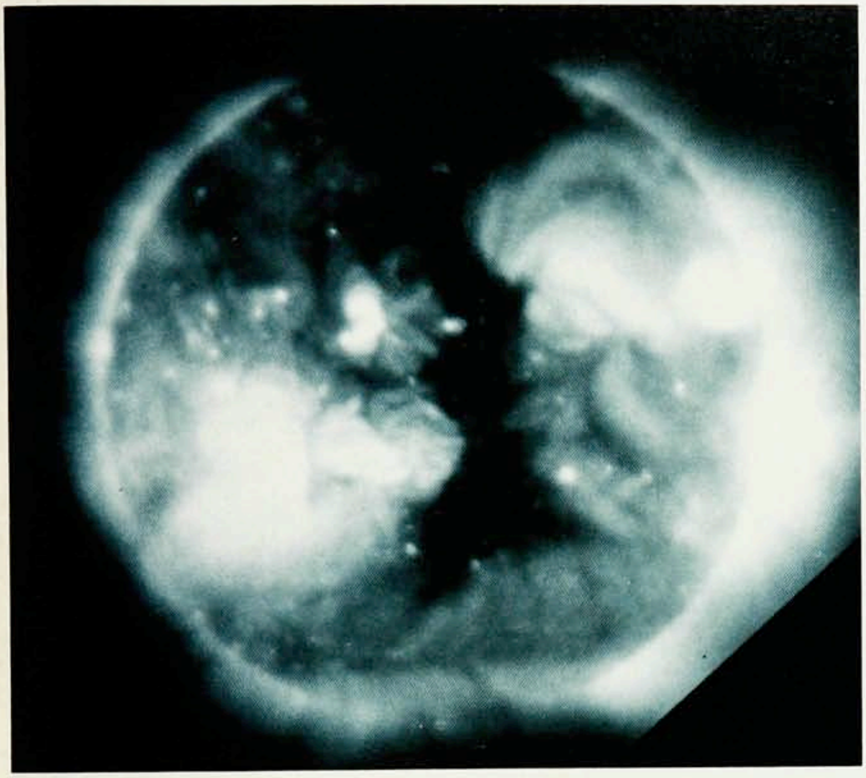


X-ray photograph of the Sun, showing the bright x-ray corona and its close association with the magnetic fields of active-region coronal loops. Coronal holes (dark regions) are gaps between active regions; x-ray bright points are the smallest x-ray coronal structures seen here. (NASA Skylab photo, courtesy of Leon Golub, Harvard–Smithsonian Center for Astrophysics.) Figure 1

x-ray-emitting regions and to get some idea of the underlying physics that causes the corona. Figure 1 is an x-ray photograph of the Sun that shows the close association of the x-ray corona with magnetic fields extending through the surface of the Sun. The magnetic fields are essential in confining the gas so that the density and temperature can increase until a detectable x-ray flux is emitted.

It is surprising, therefore, to find x-ray emission from the hotter O and B stars, because both observationally and theoretically there is no reason to think that they possess magnetic fields. Perhaps shocks and intense transient local heating originating from these stars' huge blackbody radiation fields drive supersonic gas motion to higher speed.

In this article I will discuss only the more numerous stars with surface temperatures below about 7000 K, such as the Sun. We believe stars possess magnetic fields as a consequence of internal convection. From studying the Sun we can conclude that the magnetic field plays a key role in producing the x-ray corona.[6]

Observational basis for theories

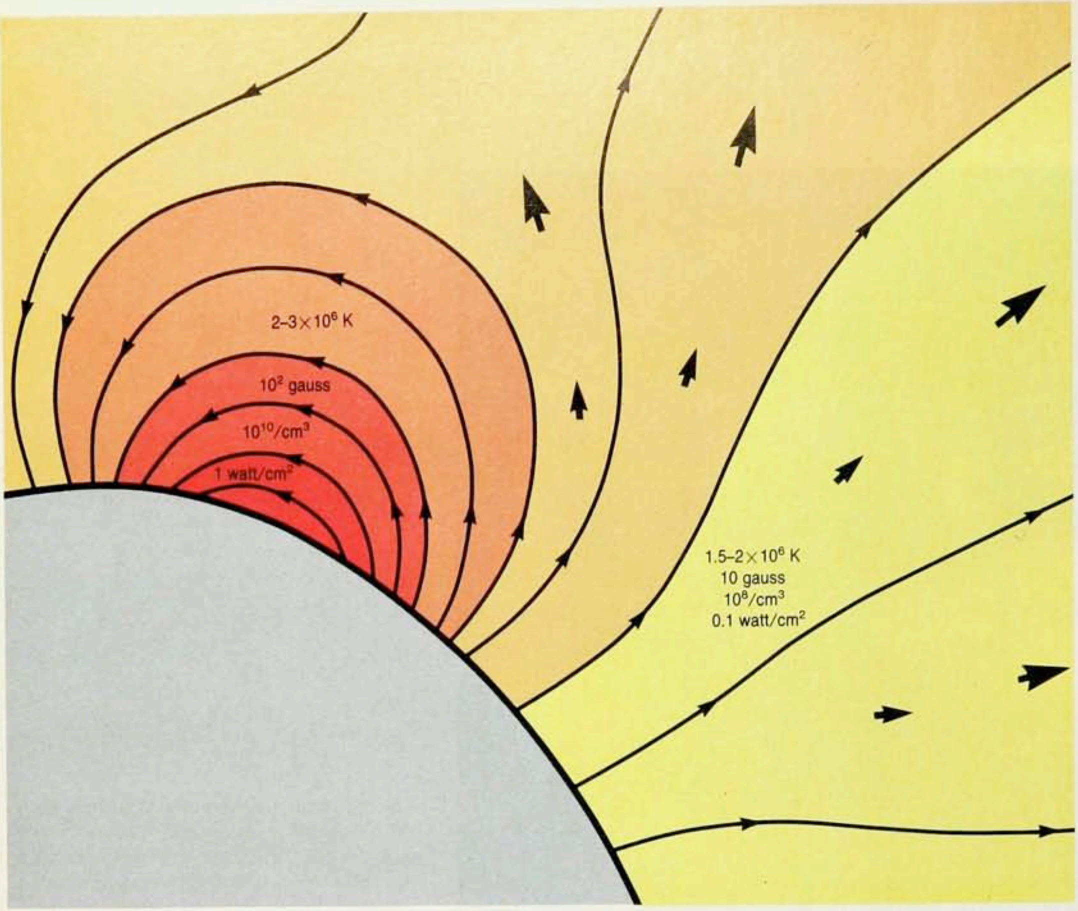
Let us consider the physical effects that compel stars to produce outer atmospheres at 10^6 K. First is the observational fact of the high temperature: 10^6 K, established first for the Sun by Bernard Lyot, Walter Grotrian and Bengt Edlén in the 1930s. Second is the thermodynamic law requiring that heat not flow continuously from the cool surface of a star ($T < 10^4$ K) to the hot corona. Somehow, then, energy is pumped from the cool surface to the hot corona.

To determine why this should happen the theorist needs detailed guidance from observation of the only star close enough to be seen and studied as something more than an unresolved blob of light. The Sun partially reveals coronal structure, which remains hidden for other stars because of their great distances. In fact, the possibility of close examination makes the Sun more exotic than any other star in the sky.

Solar observations over the last couple of decades lead us to ask a more quantitative question: Why is a star like the Sun compelled to produce regions of gas with densities of 10^{10} atoms/cm^3 and typical temperatures of $2\text{–}3 \times 10^6$ K, enclosed in re-entrant (bipolar) magnetic fields of about 10^2 gauss, which form the x-ray-emitting regions? The gas pressure is 10^{-2} times the magnetic pressure, confining the gas by a nearly force-free magnetic field. It is important to note that the x-ray corona forms in bipolar magnetic fields on all scales L from the size of the large normal active region, about 2×10^5 km, all the way down to that of the x-ray bright point, which is often associated with an ephemeral active region with a scale as small as 10^4 km. The x-ray surface brightness of the region of gas reaches approximately 1 watt/cm^2, irrespective of the dimension L of the region.

Robert Rosner, Wallace Tucker and Giuseppe Vaiana[7] have pointed out, based on detailed observational analysis, that the heat input is connected directly to the strength of the magnetic field and depends but little on anything else. It is reasonably clear that the heated gas expands upward from the surface of the Sun into the confining magnetic field until the gas density rises to where the emission of x rays balances the 1 watt/cm^2 of heat input.

Observations from Skylab show that in the x-ray dark regions, between the strong bipolar fields, the temperature is nearly as high as in the x-ray corona,



Closed and open magnetic field structures above the surface of the Sun are associated with the indicated coronal properties and are referred to as an x-ray coronal loop and coronal hole, respectively. The short arrows in this sketch indicate the motion of the gas. Figure 2

reaching 1.5–2$\times 10^6$ K, but the density rises only to 10^8 atoms/cm^3. A glance at figure 1 is sufficient to show why these regions are called *coronal holes*. They occur where the magnetic field is typically 10 gauss, and the lines of force extend far out into space, where the gentle pressure of the expanding coronal gas pushes them out to infinity. Observations of the correlation between fast solar wind speeds in space and the positions of coronal holes on the Sun indicate that the coronal holes are the origin of the faster streams in the solar wind. The coronal holes require about 0.1 watt/cm^2, most of which is consumed by the expansion of the gas to produce the solar wind.

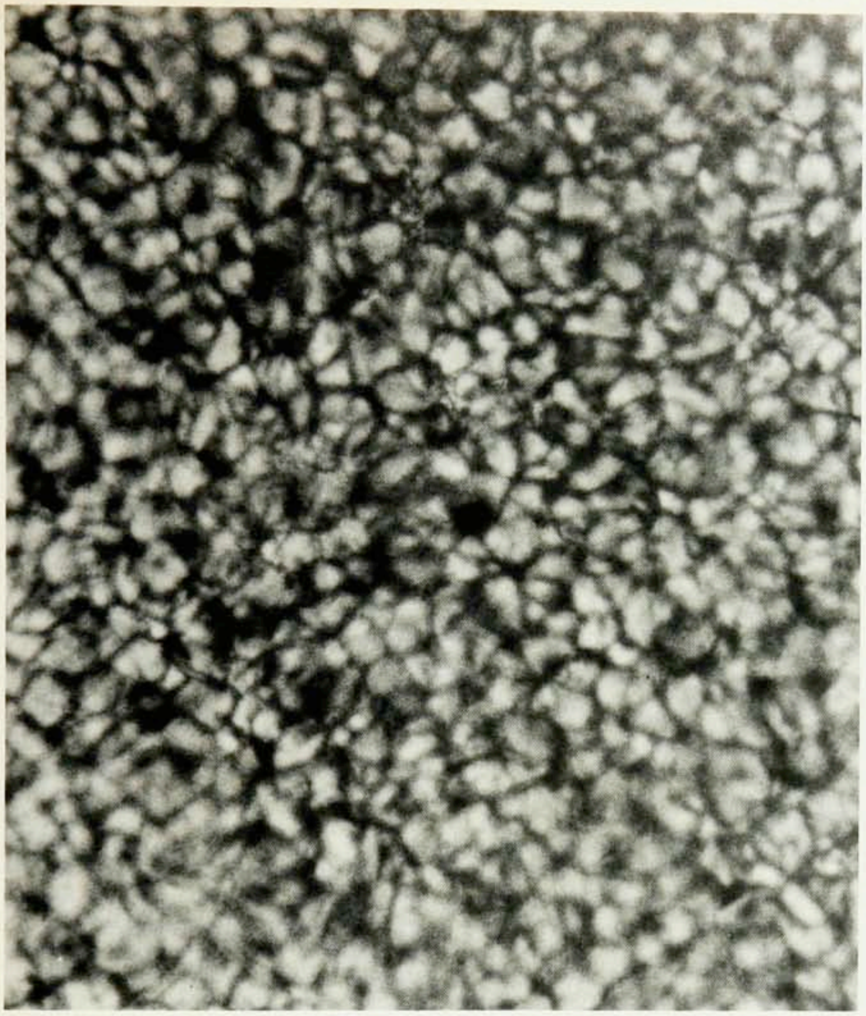
Thus from a detailed study of the Sun there appear to be two entirely different kinds of coronal regions, the x-ray corona and the coronal hole, requiring about 1 watt/cm^2 and 0.1 watt/cm^2, respectively, for their creation. The x-ray corona occurs where the gas is enclosed in strong bipolar fields, whereas the coronal hole arises in regions of weak extended field. Figure 2 is a sketch of these two distinct magnetic regions, with their vital statistics noted for quick reference.

It was generally accepted in past years that the x-ray corona is caused by the dissipation of Alfvén waves in the bipolar fields,[8] but with the recent advent of observational upper limits on wave motion in the bipolar fields of active regions, the idea has become increasingly difficult to entertain. Joseph Hollweg[9] has spelled out the necessary conditions for wave dissipation to be effective. The problem is that the Alfvén waves that reach the corona must dissipate substantially in their first pass around the bipolar field. So the problem may not have so elementary a solution. The alternative would be to assume copious fluxes of waves with periods as short as 5 sec, which would be a remarkable phenomenon in itself. Indeed, the problem is far more interesting because it leads to new aspects of classical magnetic field theory.

Convection and magnetic fibrils

To set the scene, we recall that the gas immediately below the surface of the Sun is in a state of convection. Radiation alone cannot transport the heat from the interior to the surface. When the temperature falls below about 2×10^6 K at a depth of 2×10^5 km, the interior heats up until the gas becomes convectively unstable. Convection appears at the surface as granule cells with horizontal dimensions of about 10^3 km (see figure 3 and PHYSICS TODAY, April, page 79). The lifetime of a typical granule is 5–10 minutes. The central upwelling of each cell is about 500 K hotter than the surrounding downdraft in the dark intergranular lanes. The horizontal outflow of gas from the upwelling is 1–2 km/sec at the visible surface of the Sun. Within a granule the Reynolds number is 10^{11}–10^{12}, so we expect that the convection is strongly turbulent. The granule is the largest eddy in a cascade of energy to larger wavenumbers k. This turbulence spectrum is $k^{-5/3}$, the Kolmogoroff spectrum. The smaller details of the turbulence lie below the limit of resolution of ground-based telescopes.

The magnetic fields in the tenuous corona above the surface of the Sun are



Granules (convective cells) at the surface of the Sun are shown in this white light photograph. The characteristic dimension of an individual granule is 10^3 km. (Photo courtesy of Sacramento Peak Observatory.) Figure 3

anchored in the relatively denser convective region immediately below the surface, where they are pushed and tumbled about by the highly conducting turbulent gas. One of the startling discoveries in stellar physics was the realization 15–20 years ago that the solar magnetic field, where it passes through the surface, is in an intense fibril state.[10] In fact a mean field of 10–10^2 gauss is made up of widely separated magnetic flux tubes of high field intensity, 1-2×10^3 gauss, with relatively little—if any—magnetic field between the separate fibrils. The difficulty is that the individual fibrils have diameters of 200 km or less, well below the ordinary limit of resolution of a ground-based telescope. The high field strength of the fibrils, which have a magnetic pressure about half the local gas pressure, indicates the extreme compression of the fibrils by the surrounding gas. The energy density for a given mean field is 10–10^2 times higher in the fibril state than it would be in a uniform distribution, so the phenomenon is not explained by elementary considerations. It is clear, then, that we are exploring exotic terrain, and we can expect more surprises before finishing the journey.

An initial theoretical foray

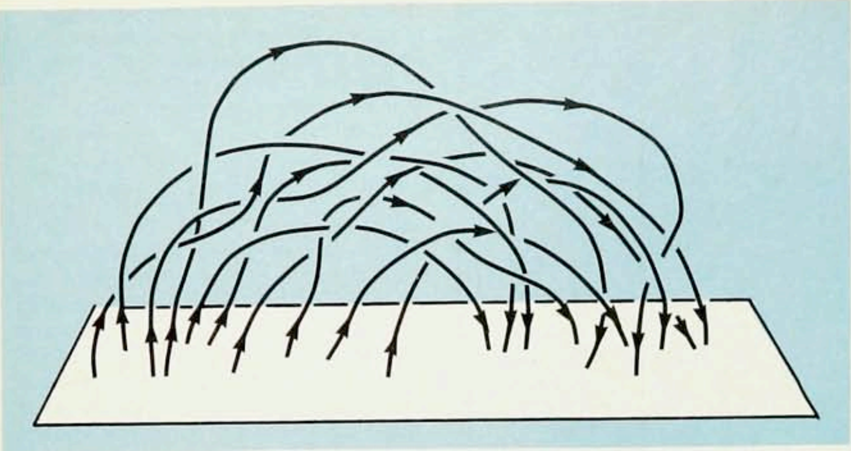
Our central question—how, in principle, is energy transferred from the solar surface at about 5800 K to the corona at 2×10^6 K?—received an answer about 40 years ago, not long after the coronal temperature was established at 10^6 K. Hannes Alfvén, Ludwig Biermann and Martin Schwarzschild each made the point that the convection represents a heat engine, which produces mechanical motions that emit Alfvén waves and sound waves up into the corona. Dissipation of these waves by viscosity, thermal conductivity and resistivity deposits heat in the tenuous coronal gas. There is then no fundamental thermodynamic limit to the temperature to which the corona may be heated.

Subsequent theoretical studies of wave propagation upward through the photosphere and overlying chromosphere have shown that sound waves, internal gravity waves and all magnetohydrodynamic waves—except Alfvén waves—are refracted or dissipated so that they do not penetrate into the corona. Their energy is deposited in the chromosphere ($\sim 2\times10^4$ K) and perhaps in the transition region ($\sim 10^5$ K). Only the Alfvén waves, representing a purely transverse disturbance in the magnetic field **B**, penetrate into the corona. As a consequence of the tension $B^2/4\pi$ in the magnetic field, the phase velocity is the Alfvén speed $V_A = B/(4\pi\rho)^{1/2}$, where ρ is the gas density. The Alfvén speed is approximately 2000 km/sec in both the x-ray corona and the coronal holes. The difficulty is that Alfvén waves are very slow to dissipate in the corona. The electrical resistivity of the gas is low and the molecular viscosity is suppressed by the magnetic field. Observations have failed to detect any wave motion in the corona, probably because the line of sight extends for 10^5 km or more through the transparent corona while the waves are expected to have transverse dimensions comparable to those of the granules ($\sim 10^3$ km). The superposition of so many independent waves cancels out the effects. Only an upper limit on the small-scale rms fluid velocity $\langle v^2\rangle^{1/2}$ is available from measurement of emission line widths,[11] namely $\langle v^2\rangle^{1/2} < 25$ km/sec in the line of sight in the x-ray corona. There is observational evidence for a comparable upper limit of about 40 km/sec for the tenuous coronal hole.[12]

Now an rms velocity $\langle v^2\rangle^{1/2}$ in each of the two directions perpendicular to the magnetic field yields an energy flux of as much as $2\rho\langle v^2\rangle V_A$ if all the waves are propagating in the same direction along the field, and as little as zero if there are equal numbers of waves propagating in opposite directions. It follows that $\langle v^2\rangle^{1/2}$ should be about 40 km/sec for the outbound waves in a coronal hole to supply the necessary 0.1 watt/cm^2. In the Wentzel–Kramers–Brillouin approximation (where the density of the atmosphere changes slowly), $\langle v^2\rangle^{1/2}$ extrapolates as $\rho^{-1/4}$, yielding 0.2 km/sec at the photosphere. This value is comfortably below the observed granule motions of 1–2 km/sec, but needs to be verified by observation of the motions of the individual magnetic fibrils.

The problem of wave dissipation

We may ask how the waves dissipate



Wrapping and interweaving of the magnetic lines of force of a bipolar magnetic region occur as a consequence of random motions of the footpoints of the field at the photosphere. Figure 4

so that their energy is diverted into heat in the coronal hole. Because the wave amplitude is small ($\langle v^2\rangle^{1/2} = 2\times10^{-2}\ V_A$), nonlinear effects are negligible. The electron conduction velocities are very small compared with the ion and electron thermal velocities, so there is no reason to expect plasma turbulence. The only known possibility is phase mixing[13] as a consequence of the variation of the Alfvén speed across the field. As the Alfvén waves propagate outward over distances of several solar radii (tens of wavelengths) the wave fronts become corrugated. It is not implausible that their dissipation follows from the eventually intense corrugation. This is the only theoretical scheme currently available for understanding the properties of the coronal hole. Obviously it cannot be verified (or denied) until observations establish the Fourier spectrum of the motions of the individual magnetic fibrils and determine a little more about the variations of the Alfvén speed across the magnetic field. It is essential to understand the process because it is probably the principal energy source for the solar wind, and therefore the basis for mass loss from the Sun and probably many other stars.

A similar wave heating may apply to the active x-ray corona.[8,9] The observational upper limit,[11] $\langle v^2\rangle^{1/2} < 25$ km/sec, allows an energy flux as large as 4 watts/cm^2 to be transported by Alfvén waves up into the x-ray corona. But there is then no obvious means to convert the Alfvén waves to heat. The wave periods are estimated to be of the general order of 10^2 sec or longer, based on the known photospheric agitation. The wavelength in the corona is then 2×10^5 km, which is comparable to the length of the lines of force in a normal active region and ten times the scale of a small x-ray bright point. The reentrant magnetic field is bipolar so the wave either is strongly dissipated in one pass up and around the field or propagates back down into the Sun at the other end of the field with no net upward energy transport.

There may be a resonance when the line of force is in tune with the input frequency[14]. Calculations by Martin Lee, Bernard Roberts and Joseph Davila[15] show that the velocities may in ideal situations build up to extraordinary levels, but only in a sheet so thin that it might escape the observational upper limit of 25 km/sec. However, the resonant amplitudes are so large (10^4 km) that we would expect a detectable disturbance in the narrow coronal filament in which the sheet occurs. But the most serious objection is that the observed rate of heating is independent of the scale of the emitting region from 10^4 km to 2×10^5 km. Such independence would require a continuous and intense wave spectrum extending from periods of 5 to 100 sec. (Joseph Hollweg[9] has worked out the necessary conditions for heating by dissipation of Alfvén waves.) In fact, the comparable x-ray brightness on all scales is the antithesis of a resonance effect. In summary, then, Alfvén waves are present in the bipolar magnetic fields of the x-ray corona, but it is not evident that they provide the major source of heat.

Coronal heating

Now if it is the form of the bipolar magnetic field—tied at each end into the photosphere—that precludes the effective dissipation of Alfvén waves, it is that same form that suggests how the heating may actually be achieved. With both ends of the field tied to the turbulently convecting photosphere it is inescapable that the shuffling and intermixing of the footpoints (individual magnetic fibrils) of the field in the turbulent photosphere soon wrap and interweave the magnetic lines of force into complicated random patterns, as sketched in figure 4. We might guess that the footpoints are kicked around with random velocities of the order of, say, 0.5 km/sec in the 1–2-km/sec motions of the granules.

The rate at which this progressive interweaving of the lines of force increases the energy of the field is illustrated[16] by the simple situation sketched in figure 5, where a single flux bundle is carried around at random with velocity **v** through an otherwise uniform field **B** of length L. After a time t the moving footpoint of the bundle has traversed a looping, meandering path of length vt perpendicular to the direction of the field **B**, with the flux bundle trailing out behind and inclined at an increasing angle θ, equal to $\tan^{-1} vt/L$, with respect to the mean field. The Maxwell stress with which the inclined bundle opposes the advance of the footpoint is $(B^2/4\pi)\tan\theta$ so the rate W (in ergs/cm^2 sec) at which **v** does work on the field is

$$W = (B^2/4\pi)v^2t/L \qquad (1)$$

With L equaling 10^5 km for a normal active region, B equaling 10^2 gauss (at the base of the corona) and v equaling 0.5 km/sec, the energy input W reaches 1 watt/cm^2 (10^7 ergs/cm^2 sec) after a time t of 5×10^4 sec, or 12 hours, at which point $\tan\theta = \frac{1}{4}$ and $\theta = 14°$. For an x-ray bright point, L is 10^4 km and the same energy input is achieved in 5×10^3 sec, with the same inclination θ of 14°.

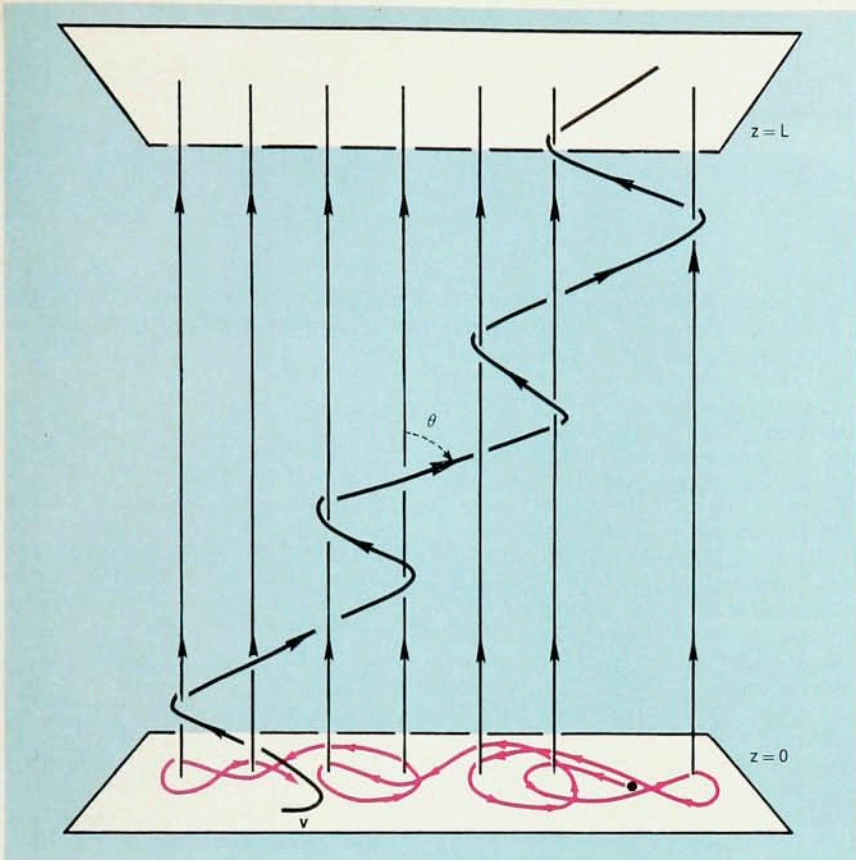
This is, of course, an input directly to the magnetic energy in the corona, except that there is now an unavoidable source of dissipation of the transverse field component $\mathbf{B}\tan\theta$. The deformation of the field is so slow ($v \ll V_A$) that the field is always near magnetostatic equilibrium,

$$0 = -\nabla p + (\nabla\times\mathbf{B})\times\mathbf{B}/4\pi \qquad (2)$$

which reduces to the simpler force-free equation

$$0 = (\nabla\times\mathbf{B})\times\mathbf{B} \qquad (3)$$

in the solar corona, where $p = 10^{-2}B^2/4\pi$. The nonlinear equation 2 or 3 has the property that even for a bounded



Single flux bundle in an otherwise uniform field **B** of length L. The bundle's footpoint is carried at random in a looping meandering path (red) with velocity **v** at $z = 0$ while the other end is held fixed at $z = +L$.
Figure 5

continuous deformation of the field at the boundaries, the mathematical solutions within the volume develop tangential discontinuities.[17] These discontinuities, represented by surfaces across which the direction of the field changes discontinuously, are current sheets where $4\pi\mathbf{j} = c\nabla\times\mathbf{B}$, as concentrated as the dissipation allows. In fact the field gradients are so large that we expect resistive tearing instabilities, neutral point reconnection and plasma turbulence excited by the high electron conduction velocity.

To spell out the mathematical nature of the solutions to equations 2 and 3, the boundary conditions involve specification of

▶ the normal component of the field at the photosphere

▶ the connectivity of the lines of force between their footpoints

▶ the pattern of interweaving of the lines of force among their neighbors as they connect between the specified footpoints.

If only the first is specified, there is always a potential solution to the problem with $\mathbf{B} = -\nabla\phi$ and $\nabla^2\phi = 0$. If, in addition, the connectivity is specified, there is always a bounded continuous solution but with $\nabla\times\mathbf{B}$ generally nonvanishing. Finally, if the pattern of interweaving is added there are generally no continuous solutions.[16,17]

Twisted flux tubes

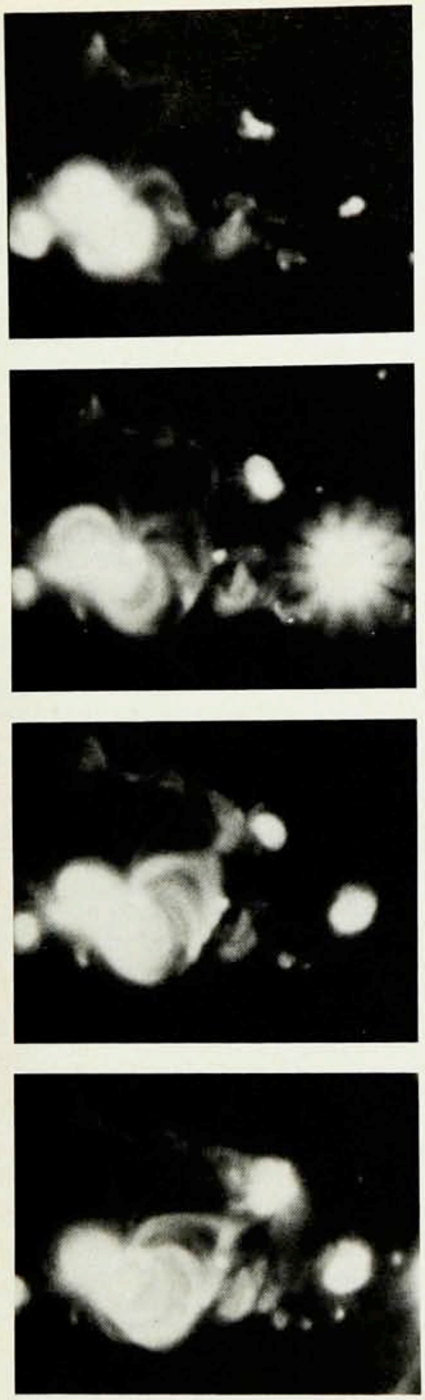
For any but the simplest configurations the solutions involve tangential discontinuities, as a consequence of the changing patterns of winding and interweaving of the lines of force along the field. A simple example is the twisted flux tube in which the twisting falls smoothly to zero toward the surface of the tube—to match smoothly and continuously a uniform external field.[18] Suppose now that the twisted tube is squashed, perhaps as a consequence of close packing with other twisted flux tubes. The result is that the lines of force at the surface of the tube become inclined to the axis of the tube by a finite angle that is approximately proportional to the squashing. Under these conditions the field of a squashed twisted flux tube does not match continuously the external field, whatever that may be. Figure 4 illustrates a more complicated situation where the domains of twisting do not fit continuously to their neighbors in most locations.

The finite resistivity of the coronal gas means that the ideal mathematical discontinuities have finite thickness, of course. The gas and the field within the thin current sheet possess no static equilibrium and tend to be squeezed out of the current sheet, thereby thinning the sheet, steepening the field gradient, enhancing the current density and increasing the dissipation. In our previous example, we assumed that until θ increases to 10°–20° after some hours of winding and interweaving, the field dissipation and reconnection associated with the current sheets do not go fast enough to keep up with the continual winding and interweaving of the field (caused by the shuffling of the footpoints). At that point a balance is struck between winding and dissipation, and the energy input to the corona is of the order of 1 watt/cm^2. Note that if the dissipation were less effective, θ would become larger and the energy input W would exceed 1 watt/cm^2! Unfortunately both the extreme complexity and the nonlinearity of the current sheets preclude a quantitative theoretical or numerical estimate of the dissipation rate. The rate necessary to provide 1 watt/cm^2 lies comfortably between the theoretical upper and lower limits on neutral-point reconnection rates.[16]

There is, of course, the observed fact that a wave of dissipation sometimes sweeps across a portion of the field, causing a burst of x-ray emission in association with the ejection of mass and extremely intense (several hundred km/sec) small-scale turbulence. This is the flare phenomenon that is observed in the x-ray emission of many stars and can be studied in detail on the Sun.

Future prospects

The basic observational requirement for all ideas on coronal heating and x-ray emission from stars is the determination of the Fourier spectrum of the motions of the magnetic fibrils in the solar photosphere. What wave periods are present—and with what amplitudes? At what rate do the individual fibrils wander among each other? Because of interest in observing



Evolution of a large (200 000 km) active-region coronal loop structure over a 36-hour period on 25–27 November 1973. NASA obtained x-ray photographs from Skylab. (Courtesy of Leon Golub, Harvard–Smithsonian Center for Astrophysics.) Figure 6

features as they vary both in time (see figure 6) and in position on the Sun, NASA has been planning the High Resolution Solar Observatory (and its predecessor, the Solar Optical Telescope) for some years now. The present HRSO project consists of a diffraction-limited 1-m mirror resolving photospheric detail down to about 100 km. If the HRSO is properly instrumented, this resolution should be sufficient to study the motions of the individual magnetic fibrils as well as their internal atmospheric structure and a variety of other small-scale effects fundamental to the physics of a star and its activity.

Ground-based telescopes may eventually be able to provide a contribution—although without the ultraviolet capability of the HRSO. Occasionally, in brief moments of good atmospheric seeing, they catch glimpses of structures as small as 200 km. But systematic study is currently possible only on scales of 500 km or more. New technology may improve this situation in the coming decade. The Smithson–Lockheed active optical system has been operated at the Vacuum Tower Telescope of the Sacramento Peak Observatory, providing consistent resolution to 200 km in fields of view containing objects of high contrast, such as solar pores. Some further improvement is needed for a decisive study of the magnetic fibrils, but that may be forthcoming in the next decade. The Large European Solar Telescope project is directed at high-resolution studies of the solar surface and may eventually contribute fundamental observational information.

The observational task will be difficult, even with the HRSO, but ultimate success is essential if we are to establish

- ▶ the structure and causes of the magnetic fibrils
- ▶ the clustering and scattering behavior of fibrils during the evolution of active regions
- ▶ the Fourier spectrum and general wandering and mixing of the individual fibrils.

Once the observations of the Sun establish what waves and what random wandering of the fibrils are to be expected in the bipolar magnetic fields, it should be possible to confirm or to refute current ideas on the origin of the Sun's x-ray corona. The development of a quantitative theory for solar x rays will serve as a starting point for interpreting the x-ray luminosities and spectra of other stars. X-ray astronomy promises to become a powerful tool for studying the magnetic field conditions and turbulence at the surfaces of other stars.

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