Review

Heating mechanisms of the solar corona

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Abstract: The solar corona is a tenuous outer atmosphere of the Sun. Its million-degree temperature was discovered spectroscopically in the 1940s, but its origin has been debated since then without complete convergence. Currently there are two classes of models; the wave theory and the microflare/nanoflare theory. Both models have merits and disadvantages, but the essential issues are nearly pinned down. Recent revival of the wave theory is one of the many contributions from Japanese solar observing satellite Hinode launched in 2006.

Keywords: Sun: corona, Sun: magnetic fields, Sun: activity, plasma physics

1 Introduction

The Sun’s visible surface, called the photosphere, is a layer of about 6000 K. The photosphere emits the so-called visible light (380–750 nm), peaking at a green wavelength of 500 nm. Averaged over its visible disk, the Sun’s emission is approximated by the black-body radiation of 5770 K. Above it is a thin layer of about 10000 K called the chromosphere; its average thickness is about 2000 km, much smaller than the solar radius of $7 \times 10^5$ km. Its name (meaning ‘color sphere’) comes from its pinkish color surrounding a dark Sun in total eclipses, due to the Hα (hydrogen Balmer-α) line of 656.3 nm. Also seen in total solar eclipses is the solar corona (Fig. 1), a pearly halo extending further out to a few solar radii. The solar corona is a tenuous outer atmosphere of the Sun, with a temperature of $1–2 \times 10^6$ K. Although the existence of the corona has long been known by total solar eclipses, its million-degree temperature was not recognized until its spectra were correctly interpreted by the physics of radiation processes in the 1940s.

Then the question was raised why such a high temperature of the corona is brought about. Since the density of the corona ($10^8–10^9$ cm$^{-3}$) is much smaller than that of the photosphere ($10^{17}$ cm$^{-3}$), the thermal energy density of the corona (although it is 200–300 times hotter than the photosphere) is negligibly small compared with the photospheric energy density. However, due to the second law of thermodynamics, heat cannot flow from the photosphere to the corona to raise the coronal temperatures hotter than the photosphere. (Conversely, the heat actually flows from the corona to the photosphere; see Fig. 8.) Since there is no plausible source of energy further out in the corona to heat up the corona, we must assume that some form of energy other than heat is supplied from below the corona to realize its million-degree temperature. This is the coronal heating problem discussed in this article.

Figure 2 shows the temperature and density structures of the solar atmosphere. A thin boundary between the chromosphere and the corona is called the transition region, where the temperature suddenly jumps from $10^4$ K to $10^6$ K. The transition region emits ultraviolet (UV) and extreme ultraviolet (EUV) radiations. The emission from the corona of $1–2 \times 10^6$ K (1–2 MK) is in the EUV to soft X-ray ranges. The visible light seen in total solar eclipses is photospheric light scattered by free electrons in the corona, and not ‘emitted’ by coronal plasmas. The emission lines seen in the visible wavelengths during total eclipses are due to a peculiar process described below, and should not be regarded as the main radiation from coronal plasmas.

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2 Discovery of a million-degree temperature of the corona

American astronomers C.A. Young and W. Harkness for the first time obtained the spectrum of the solar corona at the occasion of a solar eclipse in North America in 1869, and discovered an emission line emitted by the corona at a wavelength of 530.3 nm. Figure 3 is a spectrum of the corona which Kyoto University’s eclipse expedition photographed at the solar eclipse of 1970. In addition to emission lines from the chromosphere (Hα, Hβ, helium D3 and others), two emission lines of coronal origin are seen in red (637.4 nm) and green (530.3 nm) wavelengths; these two lines called the red line and the green line are the strongest coronal emission lines in the visible wavelengths, although currently dozens of other coronal emission lines are known.
The wavelengths of these coronal emission lines did not match those from elements known in the 19th century, and their origin had been a mystery. Many years later in the 1930s, the Swedish experimental physicist B. Edlén, in the course of studying UV emissions from highly excited ions in spark discharge experiments, determined the energy levels of Fe X (iron atom that lost 9 of its 26 electrons). In the published energy levels (Fig. 4), the German physicist W. Grotrian (famous for the so-called Grotrian diagrams of atomic energy levels) noticed a possible transition whose wavelength matches the red coronal line (637.4 nm). This transition is a forbidden transition, namely its electric dipole moment vanishes. Although higher moments (magnetic dipole moments for most of the coronal emission lines) do not vanish, they are small and the transition takes a long time. Under laboratory conditions where the density of gases is high, the emission due to this transition never takes place because collisions with particles disturb the upper-level population. In a tenuous gas like the solar corona, collisions are infrequent and ions have long-enough time for such forbidden transitions to take place. According to the suggestion from Grotrian, Edlén made a systematic series of experiments and identified the origins of many coronal lines. The coronal green line was identified as due to Fe XIV.

High excitation of ions like Fe X or Fe XIV indicates high temperature of the emitting gas. Edlén suggested that the corresponding temperature would be 250,000 K. It was Shotaro Miyamoto of Kyoto University in 1943 who for the first time theoretically arrived at the correct temperature of the solar corona. Figure 5 shows the fractions of Fe ions for given temperatures. Fe X is the most abundant ionization state for a temperature of 1 MK. Fe XIV and Fe XV are the most abundant states for a temperature of 2 MK. More modern analyses basically support these conclusions. Therefore, we can conclude that the solar corona is in a temperature range of 1–2 MK. Unfortunately, Miyamoto’s work is not widely known because it was originally published during World War II in a university bulletin in Japanese. Later in 1949 it was published in English.

In Sec. 3 we will discuss close relationships between coronal emissions and solar magnetic activities. The solar-cycle variations in coronal emission line intensities show that the intensity of the green line (Fe XIV) closely follows the sunspot number while that of the red line (Fe X) does not. This means that a 1 MK plasma represented by the Fe X emission is at the lower end of coronal temperature distribution, and the active part of the corona is in 1.5–2 MK or hotter.

![Energy levels of Fe X and the transition of the coronal red line of 637.4 nm.](image)

![Ionization fractions of various Fe ions as a function of temperature calculated by Miyamoto.](image)
3 Magnetic nature of the solar corona

In 1930 (before the high temperature of the corona was recognized), the French astronomer B. Lyot invented the coronograph, and since then the corona had been observed without waiting for total eclipses that only last for a few minutes. However, limb observations of the solar corona using coronographs or total eclipses had severe limitations. With the advent of X-ray observations of the solar corona from space, starting from the Skylab mission in 1973–74, the amount of information obtained on the corona, particularly its three-dimensional structures, had dramatically increased.

The coronal plasma, due to its high temperature, emits EUV and X-rays. Radiation in these wavelength bands is absorbed by the Earth’s atmosphere and does not reach us on the ground. However, if we launch an X-ray telescope to space (with X-ray film in old days; currently with a CCD camera) we can observe the corona. The photosphere is dark in these wavelengths, so that X-ray telescopes in orbit can see the corona on the solar disk, not only off the limb as in eclipse observations. Figure 6 (left) is an example of X-ray images of the Sun taken with the X-ray Telescope (XRT) of Hinode which was launched in 2006. The X-ray Sun is dominated by bright loop structures that delineate magnetic field lines. The hot and dense part of the corona (the active-region corona) is over the regions of strong magnetic fields, sunspots or their remnants. The background corona without active regions, the quiet-Sun corona, is less bright but is also believed to be composed of loop-like configurations with both footpoints of field lines anchored in the solar surface. Darker regions, called coronal holes, are regions of the quiet Sun whose magnetic field lines are dragged out to the interplanetary space due to the solar wind (only one foot of the field line is rooted in the solar surface).

The coronal (quiet) plasma of 1–2 MK is heated to 10–20 MK at the occasion of a solar flare. The solar flare is an explosion taking place sporadically, mostly near sunspots. Earlier observations had depended on the Hα emission coming from the chromosphere, so that the very high temperature of flares was only fully recognized after the advent of X-ray observations in the 1970s. It is notable, however, that Kin-aki Kawabata of Tokyo Astronomical Observatory deduced a 20 MK temperature in flares by using microwave radio data, as early as in 1963. The energy source of flares is believed to be the magnetic field near sunspots; The stressed magnetic field with field lines directed in the opposite directions coming closer will release magnetic energy explosively. This process called magnetic reconnection will not only heat the plasma, but also eject plasma clouds to the interplanetary space. We will come back to solar flares in the context of how the corona is heated, in Sec. 7.

4 Energy budget

The energy flux needed to heat the solar corona is summarized in Table 1. The energy balance of a coronal plasma is described by

$$n_e^2 \Lambda(T) - \text{div}(\kappa_c \nabla T) = \epsilon_H, \quad [1]$$

where \(n_e\) is the electron density, \(T\) the temperature, and \(\kappa_c\) is the thermal conductivity. The first and the second terms on the left-hand side indicate energy loss by radiation and the effect of thermal conduction (either positive or negative). On the right-hand side, \(\epsilon_H\) is the (unknown) heat input per unit volume.
The radiative loss function $\Lambda(T)$ of an optically thin plasma (emitted photons freely escape without interacting with the plasma; this is a good approximation for a tenuous plasma like the solar corona) is shown in Fig. 7 (left).

If the heating $\epsilon_H$ exceeds the energy loss, then the plasma will be heated. In the case of an open magnetic-field configuration, the plasma will expand upward by keeping the pressure $p$ constant. The density will decrease as $n_e \propto 1/T$, and the radiative energy loss will be proportional to $\Lambda(T)/T^2$. This function is shown in Fig. 7 (right), which shows that a temperature increase leads to reduced energy loss. This is a thermally unstable situation and the temperature keeps rising until a coronal temperature is reached and thermal conduction and other mechanisms stabilize the thermal runaway. (The opposite situation arises when the plasma is initially cooled, leading to condensation instability.)

In a magnetically closed volume (i.e., coronal loops), it will not freely expand so that a different situation arises. The heat conduction heats the footpoint portion of a loop which is dense, and the heated plasma expands upward and fills the loop. Therefore the density increases and the energy input is balanced by the increased radiative energy loss plus the conduction loss. In a thermal equilibrium under simplifying assumptions ($\epsilon_H$ is constant along the loop length), the following relation is derived for $T_{\text{max}}$, the temperature at the apex of the loop of length $L$,

$$T_{\text{max}} = 1.1 \times 10^6 \left( \frac{p}{1 \text{ dyn cm}^{-2}} \right) \left( \frac{L}{10^6 \text{ cm}} \right)^{1/2} \text{ [K]}, \quad [2]$$

$$\epsilon_H = 4 \times 10^{-2} \left( \frac{T_{\text{max}}}{2 \times 10^6 \text{ K}} \right)^{7/2} \left( \frac{L}{10^6 \text{ cm}} \right)^{-2} \text{ [erg cm}^{-3} \text{s}^{-1}]. \quad [3]$$

The pressure $p (\approx 10^{-1} - 10^0 \text{ dyn cm}^{-2})$ is assumed to be constant along the entire loop length; this is justified if $L$ is smaller than the pressure scale height of a 2 MK plasma of about $10^{10}$ cm. Therefore, the volume heating rate of the order of $10^{-4} - 10^{-2}$ erg cm$^{-3}$ s$^{-1}$ is required to heat the corona to 2 MK.

### 5 Heating mechanisms

Figure 8 (left) shows the energy flow to and from the corona. The energy must be carried to the corona by some non-thermal means and then thermalizes there. Before the magnetic nature of the corona was fully recognized, the agent which carries the energy was thought to be sound waves generated by turbulent convective motions near the surface (Sec. 6.1). Recently, however, it is generally believed that the magnetic field plays an important role in heating the solar corona.

Magnetic heating mechanisms are divided into AC and DC mechanisms, according to the ratio between the time scale $\tau_c$ of the convective motions which drive coronal loops at the photospheric level, and the characteristic time scale of magnetic loops, $\tau_A$. If the Alfvén speed in a loop is $V_A$ ($V_A = B/\sqrt{4\pi \rho}$ where $B$ is the magnetic field strength and $\rho$ is the density) and the length of the loop is $L$, $\tau_A$ is given by $\tau_A = L/V_A$. If $\tau_c$ is smaller than $\tau_A$, the convective motion (the driver) induces waves in the loop, which accompany AC electric currents and the Poynting

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### Table 1. Energy losses (in erg cm$^{-2}$ s$^{-1}$) from the chromosphere and the corona$^{12}$

| Region                | Quiet Sun | Coronal hole | Active region |
|-----------------------|-----------|--------------|---------------|
| Coronal temperature [K] | 1.1–1.6 x 10$^6$ | 10$^6$ | 2.5 x 10$^6$ |
| Coronal energy loss    | 3 x 10$^5$ | 8 x 10$^5$ | 10$^7$ |
| Chromospheric energy loss | 4 x 10$^6$ | 4 x 10$^6$ | 2 x 10$^7$ |

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Fig. 7. Radiation loss function $^{13}$ $\Lambda(T)$ (left) and $\Lambda(T)/T^2$ which represents the radiation loss under the condition of a fixed pressure.
flux carrying the electromagnetic energy. On the other hand, if \( \tau_c \) is larger than \( \tau_A \), the loop evolves quasi-stationarily and DC electric currents are induced. As a guideline, we may adopt \( L = 10^{8-10} \text{ cm}, \ V_A = 1000 \text{ km s}^{-1}, \) and therefore \( \tau_A = 10-100 \text{ s}. \) AC mechanisms are heating by waves, while DC mechanisms involve magnetic reconnection in the final stage of energy release.

Another important parameter that characterizes a plasma is the so-called \( \beta \)-ratio, \( \beta = 8\pi p/B^2. \) Generally \( \beta > 1 \) in the photosphere while \( \beta \ll 1 \) in the corona and in the active region chromosphere. In a low-\( \beta \) plasma (\( \beta \ll 1 \)), the density and temperature inhomogeneities are maintained along magnetic field lines due to high electrical conductivity and low cross-field thermal conductivity. An explosive release of magnetic energy in a low-\( \beta \) plasma like the solar flare inevitably leads to strong heating because the magnetic energy density \( B^2/(8\pi) \) far exceeds the initial thermal energy of coronal plasmas.

6 Heating by waves

6.1 Sound waves. The first theory proposed in 1948 to explain the million-degree temperature of the corona was the acoustic wave (sound wave) theory.\(^{15,16}\) Convective motions of gas in the photosphere (granulation) will generate pressure perturbations (acoustic or sound waves). As the waves propagate into the lower density chromosphere their amplitude will grow, and the nonlinearity in the wave propagation makes the waves steepen into shock waves. The shock waves will dissipate their energy and heat the chromosphere and the corona.

The initial theory looked satisfactory, but it was based on too optimistic estimation on the generated flux of sound waves. A quantitative model was developed later using the theoretical framework formulated by Lighthill\(^{17}\) to estimate the amount of noise generated by jet engines (he was knighted and became Sir James in 1971 according to these achievements). The power \( P \) of sound waves emitted per unit volume is expressed as

\[
P \approx \frac{\rho v^3}{L} M^{2n+1}
\]

where \( \rho \) is the density, \( v \) is the turbulent convective velocity, \( L \) is the convective eddy size, \( C_S \) is the sound speed, and \( M = v/C_S \) is the Mach number. For isotropic motions, multipole index \( n \) is equal to 2 (quadrupole emission). Therefore \( P \) is proportional to \( M^8 \) and is a sensitive function of \( M \); uncertainty in \( M \) of only 34% is amplified to a factor of 10 uncertainty in \( P \).

Granular convection in the stratified solar atmosphere may not be well approximated by isotropic turbulence. Umo\(^{18}\) extended Lighthill’s theory to gravitationally-stratified atmosphere and found that if the size of the convective eddies is of the same order of the pressure scale height of the atmosphere, the monopole \( (n = 0) \) and dipole \( (n = 1) \) emissions are more important.

6.2 Magnetic waves. As the magnetic field prevails all over the solar surface, the acoustic theory was extended to magnetic waves. In a magnetic medium three wave modes may propagate; the fast mode, the slow mode, and the Alfvén mode. The fast and slow modes are compressive and grow into shock waves, while the Alfvén wave is incompressive.

In earlier models of magnetic waves in the context of coronal heating, waves propagating along uniform magnetic fields in a one-dimensional atmosphere were considered.\(^{19}\) Kato\(^{20}\) extended Lighthill’s theory to magnetohydrodynamic waves and found that Eq. [4] with \( n = 0 \) (monopole emission) holds if \( M \) is substituted by the Alfvén Mach number \( M_A = v/V_A \) as long as \( M_A \ll 1 \). However, it was only after the magnetic structuring of the corona was discovered in the 1970s that the most intense heating turns out to be taking place in coronal loops in active regions with strong magnetic fields. Also the observations have shown that the sound-wave flux at the top of the chromosphere is about \( 10^4 \text{ erg cm}^{-2} \text{s}^{-1} \) or less, far smaller than the required energy flux to heat the corona.\(^{21}\) Wave amplitudes derived from coronal emission lines are also very small.\(^{22}\) The sound waves may be generated at the solar surface, but their flux decreases as they propagate upward, due to shock dissipation and reflection of waves. Another new finding was from the Einstein satellite which observed the X-ray emission from stars of various spectral
types. The run of observed X-ray flux versus spectral type shows a behavior different from that expected in the acoustic heating theory. In addition, the observed X-ray flux has a large scatter for stars which occupy the same place in the two-dimensional Hertzspring-Russell diagram. This suggests the existence of a third parameter that controls the coronal X-ray emission. The third parameter might very well be the magnetic field, or ultimately, the rotation of the star via dynamo effects.

On the other hand, it has been known that the width of spectral lines formed in the solar atmosphere is broader than their thermal Doppler width, indicating unresolved gas motions. This excess (nonthermal) width is also loosely called ‘the turbulent width’, although its origin may not necessarily be turbulence; small-scale waves, jet-like flows, etc., are also possible. The nonthermal width is a few km s$^{-1}$ in the chromosphere and increases up to 20–30 km s$^{-1}$ in the transition region. In the corona the behavior of the nonthermal width is more complex. The width of the green line (Fe XIV, 2 MK) decreases with height along the loops while the width of the red line (Fe X, 1 MK) increases with height (Fig. 9). At a very large height (0.3–0.5 $R_{\odot}$) they approach a constant value, and the two emission lines (1 MK and 2 MK) show the same turbulent Doppler velocity. We may imagine a picture in which a plasma heated to $T > 2$ MK and has a broader nonthermal line width comes up from the loop footpoint region and then cools to $T \approx 1$ MK and falls down.

Assuming that all the three wave modes are generated at the solar surface and propagate upward, the slow mode will most easily grow into a shock wave and will be dissipated in the chromosphere. The fast mode, once it reaches the corona, will not experience amplitude growth because the density does not decrease too rapidly along the wave path. However, the wave will develop into a shock wave due to its nonlinearity. The distance $\ell$ needed for a fast-mode wave to travel to develop a shock wave is given by

$$\ell \approx V_A \tau \frac{V_A}{V_0 \sin \theta}$$  \[5\]

where $\tau$ is the wave period, $V_0$ is the initial velocity amplitude, and $\theta$ is the angle of propagation with respect to the magnetic field direction. For $\theta \approx 0$ Eq. [5] should be replaced by

$$\ell \approx V_A \tau \left(\frac{V_A}{V_0}\right)^2.$$  \[6\]

If the nonthermal line width of coronal emission lines represents $V_0$, then $V_0 \ll V_A$ and $\ell$ is very large if $\theta \approx 0$. Therefore the fast-mode waves will propagate far up into the corona before they get dissipated by making shocks. The Alfvén waves do not develop into shocks, but their nonlinear wave-wave interaction may generate compressive waves which then dissipate their energy by shock formation. For the Alfvén waves, other mechanisms (the resonant absorption or phase mixing) are also considered as viable dissipation processes.

Whether the nonthermal width is due to Alfvén waves was examined by observing coronal loops with different orientations, and it was found that the nonthermal motions are nearly isotropic. Therefore contributions from transverse oscillations (like Alfvén waves) are minor (25% or less).

7 Microflare hypothesis

High sensitivity hard X-ray observation of the full Sun revealed many small events called microflares whose typical energy is $10^{26}$ erg, one-millionth of the energy of a largest flare, $10^{32}$ erg. Later even smaller events of the order of $10^{23}$, called nanoflares, were introduced. The basic idea is that a large number of small flare events superposed in time may show nearly a steady state. In individual flare events the plasma is heated to 10 MK or more and then cools down, leading to a time-averaged temperature of 2 MK.

In this context the important parameter is the power-law index $\alpha$ of flare occurrence rates,

$$\frac{dN}{dE} = AE^{-\alpha}.$$  \[7\]
The total amount of energy released in all the flare events of energy \( E \) is
\[
W(E_{\text{min}} \leq E \leq E_{\text{max}}) = \int_{E_{\text{min}}}^{E_{\text{max}}} \frac{dN}{dE} E dE
\]
\[
\begin{aligned}
&= \frac{A}{2 - \alpha} \left[ E_{\text{max}}^{-\alpha+2} - E_{\text{min}}^{-\alpha+2} \right]. \\
&\text{[8]}
\end{aligned}
\]

For large \( E_{\text{max}} \), \( W \) diverges if \( \alpha < 2 \), but there should be an upper limit in \( E_{\text{max}} \) imposed by the finite size of the Sun. The known maximum value for \( E_{\text{max}} \) is around \( 10^{33} \text{erg} \).

Although initial hard X-ray microflare observation indicated \( \alpha \approx 2 \), more statistics revealed that \( \alpha \) is smaller than 2, in the range of 1.5.\(^{35} \) Small flare events observed with the Soft X-ray Telescope (SXT) onboard \textit{Yohkoh} are characterized by a power-law exponent of \( \alpha \approx 1.5 \)–1.6, and their contribution to coronal heating is less than 20% of the required energy input.\(^{36} \) The results from a similar study using the X-Ray Telescope (XRT) onboard \textit{Hinode} give \( \alpha \approx 1.9 \)\(^{37} \) but are not yet conclusive because of limited data samples.

A single power-law distribution of flare events from the largest flares of \( 10^{33} \text{erg} \) to the smallest observable individual events of \( 10^{26} \text{erg} \) suggests a common physical process, which is believed to be magnetic reconnection.\(^{11} \) The magnetic energy release in a low-\( \beta \) corona naturally explains strong heating that will produce a 10 MK plasma. Even if the distribution function extends down to smaller, nanoflare ranges, the energy supplied from those smaller events is negligible because of the flat distribution of \( \alpha \approx 1.5 \).

Therefore, small-scale events must be more numerous than the extrapolated power law (Fig. 10), having a power-law index \( \alpha > 2 \). Further, they are caused by a mechanism different from the flare mechanism, because their power-law distribution is different from the flare distribution. It is also anticipated that those small-scale events will not attain a flare temperature of 10 MK (because they are not flares). Recent observation of hard X-ray spectra of an active region has given an upper limit to the amount of hot (\( T > 8 \text{MK} \)) component\(^{38} \) and also constrains the property of the small-scale events.

8 Synthetic views on coronal heating

Currently two classes of models for the heating of the solar corona can be considered (Fig. 11). In the open-field regions where the field lines have only one foot in the solar surface, it is hard to manipulate the field lines to a stressed state. The situation would be similar for quiet-Sun regions that are covered with diffuse plasma and long field lines. In these regions waves are the only means to bring energy into them. \textit{Hinode} has discovered many wave phenomena in the corona and supported this view.\(^{40} \)–\(^{42} \)

In active regions where the required energy input far exceeds the quiet regions, an agent other than waves must be sought for. Both from \textit{Hinode} Extreme Ultraviolet Spectrometer (EIS) observation\(^{43} \) and from ground-based coronagraph observations,\(^{26} \) turbulent motions of a 2 MK plasma are most active near the footpoint regions and decrease with height. EIS observation also shows the upflow
from footpoints. It is speculated that magnetic reconnection events in the footpoint regions heat the plasma to 2 MK or slightly higher, and the heated plasma will fill the coronal loops. They may eventually cool to 1 MK and fall down.

A possible origin of these footpoint activities is magnetic stress (or electric currents) imparted in the footpoints by turbulent convection during their ascent to the surface. When they emerge, their internal small-scale stress may be released by reconnection within flux tubes or they may interact and reconnect with the ambient field lines, both at a relatively low altitude (i.e., the footpoint regions). The reason why the heated plasma takes the form of closed loop configuration is rather a consequence in that the emergence of magnetic flux takes place in a bipolar configuration. If a flux tube contains large-scale electric currents, such currents may reach the corona. Or bipolar field lines may be moved by surface shear flows. These large-scale electric currents or stressed field lines mean magnetic energy stored in the coronal volume, and the stored energy may be released in the corona by magnetic reconnection. This process will produce a 10 MK or hotter plasma because it takes place in the low-β corona. The extension of the power-law distribution of flares to smaller energies (microflares or nanoflares) indicates that this is a ubiquitous process, but this flare population alone can provide at most 20% of energy required to heat the corona.

Once the emerging flux activity diminishes and the active region ages, there may be a phase in which flare contribution to the heating of the corona is increased. When the active region decayed and the magnetic field was dispersed, the field lines are only energized by surface convective motions shaking the field lines, and such quiet-region corona is heated by magnetic waves.

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Profile

Takashi Sakurai was born in 1950 in Tokyo. After graduating from the Department of Physics, Tokyo Institute of Technology in 1974, he proceeded to the graduate course of astronomy at the University of Tokyo, and obtained the D.Sc. degree in 1978. After spending half a year as a postdoctoral fellow of Japan Society for the Promotion of Science, he joined the Department of Astronomy, the University of Tokyo. In 1986 he moved to Tokyo Astronomical Observatory of the University of Tokyo, which was reformed as National Astronomical Observatory of Japan (NAOJ) in 1988. At NAOJ he served as Vice Director General from 2004 to 2012. In 2016 he retired from NAOJ and moved to the Earth-Life Science Institute, Tokyo Institute of Technology, as Administrative Director. His contributions to the research community include the editorship of Solar Physics (2006–2015) and Living Reviews in Solar Physics (2003–present), and the President of the Astronomical Society of Japan (2013–2014). Sakurai’s research interests are theoretical studies on magnetohydrodynamic phenomena seen on the Sun, as well as construction and data analysis of instruments to measure the magnetic fields on the Sun. Creation of hot atmosphere (the solar corona), acceleration of the solar wind, and storage and abrupt release of magnetic energy (solar flares) are prototypes of basic plasma processes seen widely in the universe. Sakurai is the project scientist of the Hinode mission since its launch in 2006, and has been studying the Sun’s magnetic activity using data from Hinode.