Heating Mechanisms and Radio Response from the Solar Chromosphere to Corona (Postprint)

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Abstract

Heating mechanism in the solar atmosphere (from chromosphere to corona) is one of the top-challenges in modern astronomy. The classic mechanisms can be divided into two categories: wave heating (W) and magnetic reconnection heating (X). Both of them still face some problems currently difficult to overcome. Recently, we proposed a new mechanism, called magnetic-gradient pumping heating (MGP, or P) which seems to overcome those difficulties, but still lacks sufficient observational evidence. Which one really explained the physics of hot corona exactly? How can observations be used to identify and verify the heating mechanism? Since different heating mechanisms will generate non-thermal particles from different accelerations and experience different propagations, they will have different responses in the broadband spectral radio observations. Among them, the non-thermal electrons from W mechanisms are closely related to shock-wave acceleration, and their radio response should be a group of spike bursts with random distribution of drifting rates; the non-thermal electrons from X mechanisms are accelerated by reconnecting electric field with bidirectional flow, and their radio response should be type III pairs or spike pairs; P mechanism will produce energetic particle upflows, and their radio response should be unidirectional fiber bursts with moderate negative drifting rates. Therefore, the heating mechanism can be identified and verified from the broadband dynamic spectral radio observations. Additionally, using high-resolution radioheliographs and spectral-imaging observations, the heating mechanisms in different regions can be identified and verified separately, thereby demonstrating the physical essence of the hot corona.

Full Text

Preamble

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Heating Mechanisms and Radio Response from the Solar Chromosphere to Corona

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Abstract

The heating mechanism in the solar atmosphere (from chromosphere to corona) represents one of the foremost challenges in modern astronomy. Classic mechanisms can be divided into two categories: wave heating (W) and magnetic reconnection heating (X), both of which currently face significant unresolved difficulties. Recently, we proposed a new mechanism called magnetic-gradient pumping heating (MGP, or P), which appears to overcome these challenges but still lacks sufficient observational evidence. Which mechanism truly explains the physics of the hot corona? How can observations be used to identify and verify the heating mechanism? Since different heating mechanisms generate non-thermal particles through different acceleration processes and propagation paths, they produce distinct responses in broadband spectral radio observations. Specifically, non-thermal electrons from W mechanisms are closely related to shock-wave acceleration, producing radio responses in the form of spike bursts with randomly distributed drifting rates. Non-thermal electrons from X mechanisms are accelerated by reconnecting electric fields with bidirectional flows, producing type III pairs or spike pairs in radio observations. The P mechanism produces energetic particle upflows, yielding unidirectional fiber bursts with moderate negative drifting rates. Consequently, heating mechanisms can be identified and verified through broadband dynamic spectral radio observations. Additionally, using high-resolution radioheliographs and spectral-imaging observations, different regions can be identified and verified separately, thereby revealing the physical essence of the hot corona.

Key words: Sun: radio radiation –Sun: corona –Sun: general

1. Introduction: Coronal Heating—A Century-Long Scientific Challenge

As is well known, all energy released from the solar surface outward ultimately originates from hydrogen nuclear fusion in the Sun’ s core, where temperatures exceed 1.5×10^7 K. After leaving this region, the temperature gradually decreases to approximately 5700 K near the photosphere, where the plasma becomes weakly ionized. However, more than 80 years ago, researchers were surprised to discover that the Sun’ s outer atmosphere (from chromosphere to corona) is much hotter than the underlying photosphere, with coronal temperatures exceeding 10^6 K. Without questioning the second law of thermodynamics, we must conclude that non-thermal heating processes operate in the solar outer atmosphere to maintain such high temperatures. What mechanism produces these heating processes? This is the coronal heating mystery.

Why must we study coronal heating? First, the rapidly warming transition region (TR) and the extremely hot, strongly ionized, magnetically frozen coronal plasma constitute the source region for various solar activities. Naturally, the heating processes dominate the generation of solar activities (including flares, coronal mass ejections (CMEs), jets, etc.). Second, the hot TR and corona also serve as the source of the solar wind, with heating processes directly controlling the initiation, formation, and evolution of the solar wind. Therefore, elucidating the physical nature of solar atmospheric heating is a crucial prerequisite for understanding the origins of solar activities, solar wind, and the occurrence of disastrous space weather events. Third, coronal heating involves the generation, transport, and dissipation of energetic particles in magnetized plasma—a fundamental principle in plasma physics that provides important insights for magnetic confinement nuclear fusion research.

The heating energy requirement is approximately 300 W m^{-2} above solar quiet regions (QRs), 800 W m^{-2} above coronal holes (CHs), and 10^4 W m^{-2} above active regions (ARs). For the chromosphere, due to its higher radiative losses, the heating energy requirement is much greater: approximately 4000 W m^{-2} above QRs and CHs, and 2×10^4 W m^{-2} above ARs (Withbroe & Noyes 1977).

Over the past 80+ years, various heating mechanisms have been proposed to explain the formation of the hot corona. Classic mechanisms can be broadly classified into two types: wave heating (W mechanisms) and magnetic reconnection heating (X mechanisms) (Narain & Ulmschneider 1996; Walsh & Ireland 2003; Klimchuk 2006, 2015). However, each faces significant unresolved difficulties. In recent years, the heating effects of spicules and small-scale jets have received increasing attention (De Pontieu et al. 2004, 2011; Ji et al. 2012; Samanta et al. 2019; Chen et al. 2022; Chitta et al. 2023). Tan (2014) proposed a new mechanism called magnetic-gradient pumping heating (MGP, or P mechanism). Despite numerous proposed heating mechanisms, this problem remains unsolved, making it a century-long scientific challenge (Kerr 2012). What is particularly confusing is that, until now, no practical method exists to identify and verify different heating mechanisms through observations. These facts seriously constrain all efforts to address this scientific challenge (Leonardo & Fidel 2023).

Based on differences in the generation and propagation of non-thermal energetic particles associated with different heating mechanisms, we discuss here the possible physical picture of plasma heating from the chromosphere to the corona, and the possibility of using broadband dynamic radio spectral observations to identify and verify these mechanisms. Section 2 discusses the main characteristics, generation, and propagation of non-thermal energetic particles, along with the primary limitations of various heating mechanisms. Section 3 presents the possible radio response patterns associated with different mechanisms that may help identify and verify them. Conclusions are summarized in Section 4.

2. Physical Framework of Heating Mechanisms

We first discuss the main characteristics, advantages, and challenges of different heating mechanisms, focusing particularly on the generation and propagation of energetic particles in different heating processes to identify observable evidence for distinguishing these mechanisms.

2.1. The Classic Heating Mechanisms

Currently, classical coronal heating mechanisms can be roughly divided into two categories: wave heating and magnetic reconnection heating. We discuss their main physical processes and basic characteristics of energy release separately.

2.1.1. Wave Heating (W Mechanism) When the coronal heating problem was first raised, wave heating was the first mechanism considered. Strong convection and turbulence in the photosphere can trigger various waves in the solar atmosphere, such as sound waves (Schwarzschild 1948), Alfvén waves (Alfvén 1947; Jess et al. 2009), and magnetoacoustic waves (Choudhuri et al. 1993). If these waves can propagate upward to the corona and dissipate there, they could provide sufficient energy to heat the corona (Heyvaerts & Priest 1983; Davila 1987; Lee & Wu 2000; Cranmer et al. 2007; De Pontieu et al. 2007; Ji et al. 2021; Yuan et al. 2023). Cranmer et al. (2007) developed a series of self-consistent models for plasmas along open magnetic flux tubes rooted in CHs, streamers, and ARs to demonstrate chromospheric heating driven by empirically guided acoustic waves and coronal heating from Alfvén waves. Rappazzo et al. (2007) determined that MHD anisotropic turbulence should be the physical mechanism responsible for transporting energy from large scales, where it is injected by photospheric motions, to small scales, where it is dissipated. Jess et al. (2009) reported the detection of Alfvén waves in the low solar atmosphere with sufficient energy flux to heat the corona. Asgari-Targhi et al. (2013) and Van Ballegooijen et al. (2017) constructed three-dimensional MHD models to simulate the spatial and temporal dependence of coronal loop heating by Alfvén waves.

However, a critical question remains: How does wave energy dissipate into thermal energy in the surrounding plasma? One important wave dissipation mechanism occurs in regions where plasma temperature and density change rapidly, causing linear waves to transform into shock waves. These shock waves can accelerate charged particles and generate non-thermal energetic particles, thereby heating the plasma. This is the so-called linear wave-shock wave mechanism.

The energy flux carried by a linear wave can be expressed as:

$$F = \frac{1}{2}\rho V^2 u$$

where ρ is the plasma density, V is the disturbance velocity amplitude of the linear wave, and u is the propagation speed, which is expressed as follows for sound waves (v_s), Alfvén waves (v_A), and magnetoacoustic waves (v_m), respectively:

$$v_s = \sqrt{\frac{k_B T}{m_i}}$$

$$v_A = \frac{B}{\sqrt{\mu_0 \rho}}$$

$$v_m = \sqrt{\frac{1}{2}\left(v_s^2 + v_A^2 \pm \sqrt{(v_s^2 + v_A^2)^2 - 4v_s^2 v_A^2 \cos^2\theta}\right)}$$

where k_B is the Boltzmann constant, T is the temperature, m_i is the ion mass, B is the magnetic field strength, and θ is the angle between the propagation direction and magnetic field. In the expression for magnetoacoustic waves (v_m), when the $+$ sign is taken, it represents a fast magnetoacoustic wave, and when the $-$ sign is taken, it represents a slow magnetoacoustic wave.

When a linear wave generated from photospheric turbulence propagates upward, its energy flux F can be regarded as approximately conserved. The disturbance velocity amplitude can then be expressed as:

$$V = \sqrt{\frac{2F}{\rho u}}$$

From the photosphere to the corona, both density and magnetic field strength decrease rapidly while temperature continues to increase. Overall, the value of ρu decreases, leading to an increase in V. When $V > u$, the linear wave transforms into a nonlinear sawtooth-like shock wave. Shock waves are nonlinear dissipative structures that can both heat plasma and accelerate charged particles to form non-thermal energetic particle beams.

Figure 1 presents the variations of propagation speed (black solid curves) and disturbance velocity amplitude (purple dashed curves) with height above the solar photosphere for sound waves, Alfvén waves, fast waves, and slow waves. The density and temperature values come from the well-known literature (Vernazza et al. 1981), and the magnetic field strength (B) is obtained from potential field extrapolation assuming a simple value of 100 G at the photospheric footpoint (B_0), which is typical around network regions in QRs and CHs. For each wave type, we provide results for three energy flux scenarios: $F = 5$, 50, and 500 W m^{-2}.

Figure 1 reveals several key facts: (1) It is almost impossible for all linear waves originating from photospheric convection to reach the corona; most transform into nonlinear shock waves in the chromosphere and lower TR. Consequently, non-thermal energetic particles associated with wave heating mechanisms should be accelerated primarily in the chromosphere and lower TR. (2) The larger the wave energy flux, the lower the height at which upward propagation ceases. Only when the energy flux is very low can a small fraction of waves penetrate through the TR and reach the corona, but this amount of wave energy is insufficient to heat the corona. (3) We can also vary the magnetic field B_0 in Figure 1, and find that when B_0 increases, the propagation height of Alfvén waves and fast magnetoacoustic waves also increases, and the energy flux reaching the corona gradually increases. For example, when $B_0 = 1000$ G and $F = 1$ W m^{-2}, the fast wave can propagate upward to a height of 5000 km, near the bottom of the corona. Since the heating energy requirement should be approximately 10^4 W m^{-2} in the corona above ARs, this indicates that in ARs, only a very small fraction of linear waves originating from the photosphere can propagate into the corona before being converted into shock waves and dissipated.

However, many observations indicate the existence of various waves in the corona (Van Doorsselaere et al. 2020; Hashim et al. 2021). Two possibilities exist: First, these waves may originate from leakage in a few very strong magnetic field regions, which would contribute only a tiny fraction to coronal heating. Second, these waves may not originate from photospheric convection but are instead triggered by various eruptions in the corona, such as flares, microflares, or even nanoflares. In fact, coronal heating by such waves is part of magnetic reconnection heating, which we discuss in the following section.

These facts indicate that whether sound waves, magnetoacoustic waves, or Alfvén waves, their heating effect is limited to the solar chromosphere and low TR, and they are essentially ineffective in the higher solar atmosphere.

2.1.2. Magnetic Reconnection Heating (X Mechanisms) As frequently observed, solar flares can release large amounts of energy into surrounding plasma through magnetic reconnection. For example, Lu et al. (2024) found that continuous magnetic flux emergence in ARs might drive magnetic reconnections that release energy impulsively but persistently over time on average, heating numerous substructures to 10^7 K. Besides powerful flares, Jin et al. (2021) reported a microflare event on the quiet Sun that released 1.3×10^{27} erg of thermal energy and heated the corona to 5.8×10^{6} K. We might assume that a series of flares of various scales exist in the solar atmosphere, including powerful X-class flares, M-class flares, C-class flares, and smaller B-class flares, A-class flares, and even microflares, nanoflares, and picoflares. The energy they release can heat the solar chromosphere, TR, and corona.

Although the scales of these flares vary greatly, their released energy essentially involves magnetic reconnection around current sheets in the source region, which accelerates charged particles and heats the surrounding plasma. This heating mechanism is also known as magnetic reconnection heating, DC mechanisms, or nanoflare models (Parker 1988; Hudson 1991; Sturrock 1999); here we refer to it as the X mechanism. Many researchers have studied the possibility of this mechanism heating the corona through observations and numerical simulations (Testa et al. 2014; Tian et al. 2014; Bradshaw & Klimchuk 2015; Berghmans et al. 2021; Chen et al. 2021).

If the energy released by each microflare is approximately on the order of 10^{19} J, the occurrence rate of microflares across the entire solar surface must be >1000 s^{-1} to heat the corona (Moore et al. 1991). However, all statistical observations to date indicate that the actual occurrence rate of microflares is less than 10 s^{-1} (Hudson 1991; Jiang et al. 2015). This suggests that X mechanisms likely provide only a small contribution to coronal heating. Additionally, the relationship between event frequency $f(E)$ and energy E follows a power law:

$$f(E) \propto E^{-\alpha}$$

It has long been established that the power-law index α is a strong indicator of whether the X mechanism is an important coronal heating mechanism. If the X mechanism is to provide sufficient heating, it requires $\alpha > 2$ (Hudson 1991; Aschwanden & Freeland 2012). However, Crosby et al. (1993) obtained $\alpha = 1.53 \pm 0.02$ for events with energies in the range 10^{21}–10^{24} J. Shimizu (1995) estimated α to be between 1.5 and 1.6 for AR small-scale events with energies in the range of 10^{20}–10^{22} J. These results seem to indicate that the X mechanism cannot be the dominant heating mechanism in the solar corona. However, contrary results have also been reported. For example, Parnell & Jupp (2000) obtained $\alpha > 2.0$ for events with energies in the range of 10^{16}–10^{19} J, implying that the X mechanism may dominate heating of the solar quiet corona. These facts have once again puzzled us: How much does the X mechanism contribute to coronal heating?

With increasingly high-resolution imaging observational facilities coming online, vast amounts of observational data have been accumulated, and researchers continue conducting more extensive and in-depth statistical studies hoping to obtain more accurate conclusions. A very recent statistical study showed $\alpha = 1.63 \pm 0.03$ (Mason et al. 2023), indicating that the contribution of the X mechanism to coronal heating is likely less than 20%. More than 80% of the required energy for coronal heating should still be provided by W or other heating mechanisms. We believe this latest statistical result may be closer to the truth about the Sun, and the X mechanism may indeed play only a minor role in heating the entire solar atmosphere.

Additionally, since neutral particles do not respond to magnetic fields, magnetic reconnection does not easily occur in the low chromosphere with weak ionization at low temperatures. Correspondingly, X heating is difficult to achieve in the low chromosphere. X heating can only occur in the strongly or fully ionized plasma of the upper chromosphere, TR, and corona.

2.2. New Heating Mechanism

Is there another heating mechanism besides the W and X mechanisms? In recent years, new mechanisms and ideas have been constantly proposed, such as spicules, small-scale jets, EUV cyclones, and the magnetic-gradient pumping mechanism.

2.2.1. Spicules, Small-scale Jets, and EUV Cyclones Recently, with a series of high-resolution solar telescopes coming online, more characteristics related to spicules and small-scale jets have been discovered. Their heating effect on the chromosphere and corona has received increasing attention, and researchers even suspect this may represent a new heating process (De Pontieu et al. 2004, 2011; Samanta et al. 2019; Chitta et al. 2023). De Pontieu et al. (2004) proposed that p-modes might leak sufficient energy from the global resonant cavity into the chromosphere to power shocks and drive upward flows to form spicules. Furthermore, De Pontieu et al. (2011) revealed a ubiquitous coronal mass supply from chromospheric plasma in fountain-like jets or spicules that accelerate upward and may heat the corona. Zhang & Liu (2011) demonstrated that ubiquitous EUV cyclones rooted in rotating network magnetic fields in the quiet Sun might provide an effective way to heat the corona. Ji et al. (2012) revealed unexpected complexes of ultra-fine, hot magnetic channels linking the photosphere to the base of the corona with upward hot plasma jets.

When we carefully analyze these observational features, we find that most spicules and small-scale jets are actually still closely related to certain magnetic reconnection or cancellation events, and they likely represent a new manifestation of X heating (Samanta et al. 2019; Chitta et al. 2023). Some spicule and small-scale jet events are related to certain wave processes originating from the photosphere (De Pontieu et al. 2004; Cranmer & Woolsey 2015). Moreover, the MGP mechanism discussed in the next section can provide a reasonable explanation for some spicules, jets, and ultra-fine hot channels. Therefore, although these small-scale activity events do contribute to heating the solar atmosphere, they do not physically represent an independent heating mechanism.

2.2.2. Magnetic-Gradient Pumping Mechanism (P Mechanism) Magnetic gradients are commonly present in the solar atmosphere above ARs, magnetic networks in QRs, and even CHs. In this case, the magnetic-gradient force drives the aggregation of energetic particles in weak-field regions (Tan 2014; Tan et al. 2020). The force balance can be expressed as:

$$F_t = mg(h) - G_B \varepsilon_t$$

where $G_B = -\frac{1}{B}\frac{dB}{dh}$ is the relative magnetic gradient, ε_t is the transverse kinetic energy of charged particles, $mg(h)$ is the gravitational force at height h above the solar surface, and $G_B\varepsilon_t$ is the magnetic-gradient force. Since magnetic field strength in the solar atmosphere always decreases with height h, the direction of the magnetic gradient (G_B) is always downward, while the direction of the magnetic-gradient force is always upward. This feature is independent of the magnetic field direction itself.

When $F_t = 0$, $\varepsilon_t = \varepsilon_0(h) = \frac{mg(h)}{G_B}$, the particle resides around height h, called resident particles. Here, $\varepsilon_0(h)$ is a critical kinetic energy that is a function of height h. At each height h, the temperature is dominated by $\varepsilon_0(h)$, which is determined by the local gravitational force $mg(h)$ and the relative magnetic gradient G_B. Generally, the relative magnetic gradient G_B decreases slowly in the chromosphere, rapidly in the TR, and then slowly again in the corona. Consequently, temperature increases slowly in the chromosphere, rapidly in the TR, and slowly again in the corona.

Additionally, as G_B decreases with increasing height faster than gravity $mg(h)$, temperature T increases with height. This variation coincides perfectly with actual conditions in the solar atmosphere. According to this principle, the formation of type II spicules (De Pontieu et al. 2011) and ultra-hot channels (Ji et al. 2012) can be precisely explained.

When $F_t < 0$, $\varepsilon_t < \varepsilon_0(h)$, the particle sinks below height h, called confined particles. This indicates that lower-energy particles always stop and remain in the lower atmosphere.

When $F_t > 0$, $\varepsilon_t > \varepsilon_0(h)$, the particle moves upward to escape from height h, called escaping particles. This indicates that higher-energy particles are pumped upward to form energetic particle upflows that carry energy to higher atmospheric layers.

Essentially, the MGP heating mechanism represents a sorting process without particle acceleration and therefore without magnetic energy release. The magnetic gradient separates energetic particles from lower atmospheric plasma in thermal equilibrium and drives them upward. The upward escaping energetic particles accumulate in the upper atmosphere, thereby increasing its temperature. This process is somewhat analogous to mineral processing: a small amount of rich ore is extracted from a large amount of poor ore while the total ore quantity is conserved. Preliminary estimates indicate that the energy carried by upward escaping energetic particles is sufficient to heat and maintain the hot

TR and hotter corona (Tan 2014). The MGP mechanism may provide a reasonable explanation for the formation of ubiquitous type II spicules (De Pontieu et al. 2011).

For fully ionized magnetized plasmas, the MGP mechanism can operate very naturally. However, for partially or weakly ionized plasmas such as chromospheric plasma, collisional processes can easily cancel out the MGP process due to the presence of large numbers of neutral particles. Therefore, the optimal regions for the MGP mechanism to operate are the highly ionized upper chromosphere, TR, and corona.

2.3. Overall Physical Image of Heating from the Chromosphere to Corona

The three heating mechanisms all depend on the magnetic field from the chromosphere to the corona, but their dependence on the magnetic field differs, and the corresponding heating processes are completely different. For W heating, the magnetic field provides a waveguide, though its role in wave dissipation varies among different dissipation mechanisms. For X heating, changes in magnetic field topology are fundamental to magnetic energy release. In the P mechanism, the magnetic field provides a pumping channel, and the entire heating process does not change the strength or configuration of the magnetic field, nor does it release magnetic energy. Instead, the magnetic-gradient force redistributes thermal particles in the lower atmosphere according to their energy, with high-energy particles converging toward weak-field regions in the corona.

These differences also indicate that different heating mechanisms can operate in different physical environments. In fact, the physical conditions differ significantly from the chromosphere to the TR to the corona. As shown in Figure 2, the chromosphere has a slowly rising temperature, and the gas is weakly ionized, with ionization degrees ranging from negligible (0.01%) to about 10%. The TR has a rapidly increasing temperature, and the gas is essentially strongly ionized. The corona’ s temperature rises slowly again, and the gas becomes a very thin, fully ionized plasma. These facts imply that the coronal heating problem actually comprises three closely related and interdependent sub-problems: chromospheric heating, TR heating, and coronal heating.

Based on the above discussion, we attempt to establish the following physical picture of solar atmospheric heating:

1. In the chromosphere, photospheric convection can excite various waves—including sound waves, magnetoacoustic waves, and Alfvén waves—that transport energy upward. As discussed in Section 2.1.1, these waves have difficulty penetrating through the TR to reach the corona. Additionally, the weak partial ionization of the dense low chromosphere makes it difficult for X and P heating processes to operate. Therefore, we can preliminarily infer that various waves (marked as W in Figure 2) originating from photospheric convection may dominantly heat the chromosphere, resulting in

the slow temperature increase. Likely in the upper chromosphere, where temperature increases beyond 10^4 K and ionization becomes high enough, X heating and P heating may provide certain contributions (marked as x and P in Figure 2).

2. In the TR, due to strong ionization and strong magnetic fields, P heating should be dominant (marked as P in Figure 2), while W heating can provide a minor contribution in the lower TR. Various scales of X heating (small flares, microflares, nanoflares, etc.) also provide some contributions here.
3. In the corona, the gas becomes fully ionized, the magnetic field becomes relatively weak, and the dominant heating mechanisms should be P heating and X heating (flares, small flares, microflares, etc.), which provides a minor contribution, while W heating can be neglected.

In Figure 2, we have marked the possible heating mechanisms in different regions below the temperature curve with letters, where uppercase letters (W, P) indicate the dominant mechanism and lowercase letters (w, x, p) indicate secondary heating mechanisms. Here, W and w signify wave heating, P and p represent the MGP heating mechanism, and x denotes magnetic reconnection heating.

3. Radio Emission Responses to Different Heating Mechanisms

In the previous section, we demonstrated that various heating mechanisms (W, X, and P) operate in different regions with different combinations. How can we distinguish and identify them observationally? Any heating mechanism should include two aspects: thermal effects (temperature increase) and non-thermal effects (generation and propagation of energetic particles). In different heating mechanisms, observed characteristics of thermal processes are very similar (such as images at infrared, optical, UV, and EUV wavelengths), making them difficult to distinguish. However, non-thermal processes differ significantly. Due to substantial differences in the generation and propagation of energetic charged particle flows from different heating mechanisms, vastly different emission signals inevitably appear in radio observations, making it possible to distinguish heating mechanisms accordingly.

Radio emission responds clearly to almost all processes in astrophysical plasmas, including thermal phenomena, non-thermal phenomena, and magnetic field variations. Radio emission is particularly sensitive to non-thermal energetic electrons. Different particle acceleration and propagation processes produce different responses in broadband dynamic radio spectral observations (Dulk 1985; Bastian et al. 1998; Gary 2023). Solar radio emissions cover a wide frequency range spanning up to 7 orders of magnitude from submillimeter waves (>1 THz) to kilometer waves (<300 kHz), with corresponding source regions covering the solar photosphere, chromosphere, TR, corona, and even interplanetary space. Emission mechanisms include bremsstrahlung and cyclotron emission (CE) from thermal or low-energy non-thermal electrons, and gyrosynchrotron emission (GE) and coherent plasma emission (PE) from non-thermal electrons. As discussed in Section 2, energetic particle generation varies among different coronal heating mechanisms, which may exhibit different spectral patterns in radio observations, including duration, bandwidth, lifetime of individual bursts, frequency drifting rate and its distribution of positive and negative signs, etc.

3.1. Radio Response of W Mechanisms

When W mechanisms play the main role in coronal heating, linear MHD waves (sound waves, Alfvén waves, fast and slow magnetoacoustic waves) must transform into shock waves to dissipate energy and heat the plasma. It is precisely because of shock wave formation that charged particles can be accelerated, producing non-thermal energetic particles. Shock wave acceleration of charged particles exhibits very complex randomness, resulting in randomness in the propagation direction of generated non-thermal particles after leaving the acceleration site. The corresponding radio emission should be a large group of spike bursts with short lifetime (<1 ms), narrow frequency bandwidth (around 1% of the central frequency), and random distribution of positive and negative signs of fast frequency drift rate, similar to spike groups associated with flare terminal shock waves (Chen et al. 2015). The left panel of Figure 3 shows an example of a randomly distributed spike group (RDSG) that occurred during the decay phase of a powerful X-class flare on 2005 January 20.

As discussed in Section 2.1, it is difficult for various waves originating from photospheric convection to penetrate through the TR, and most transform into shock waves in the chromosphere and lower TR. Therefore, non-thermal electrons associated with W heating generate and propagate mainly in the chromosphere and lower TR. They can generate radio emission through two mechanisms: GE and PE (Dulk 1985). In the chromosphere, electron density (n_e) ranges between 10^{17} m^{-3} and 4×10^{17} m^{-3} (Vernazza et al. 1981, Figure 2), and magnetic field strength can be assumed to range from 100 to 1000 G. The non-thermal electrons can be regarded as mildly relativistic with kinetic energy of 10-300 keV. The associated PE (including fundamental and second harmonic) should be in the frequency range of 2.8-11.5 GHz, and GE with harmonic numbers of 10-100 will be in the frequency range of 2.8-280 GHz. In the TR, electron density (n_e) ranges between 2×10^{15} m^{-3} and 10^{17} m^{-3} (Figure 2), and magnetic field strength will be slightly weaker than in the chromosphere, with typical values of about 50-500 G. With these parameters, the associated PE will be in the frequency range of 400 MHz-5.7 GHz, and GE should be in the frequency range of 1.4-140 GHz. In reality, there are not many non-thermal electrons with energies exceeding 300 keV in the chromosphere and TR, and the corresponding emission is weak. It is difficult for the harmonic number of GE to exceed 70-80, and the corresponding upper limit of emission frequency is always lower than 100 GHz. Due to lower electron density and weaker magnetic field in the corona compared to the TR, if we can observe RDSG below the above frequency range during quiet Sun conditions, it would indicate that W heating also exists in the corona.

3.2. Radio Response of X Mechanisms

When the X mechanism plays the main role in heating the corona, numerous small-scale current sheets will inevitably appear in the TR and corona. Here, energetic non-thermal particles are accelerated through the reconnecting electric field, forming many bidirectional non-thermal particle flows (Yu et al. 2020). The corresponding radio emission will have a bidirectional fast-drifting spectral structure appearing in burst pairs with opposite frequency drifting rates, such as type III pairs (Aschwanden & Benz 1997; Tan et al. 2016) or spike pairs (Tan 2013). In each burst pair, the separation frequency between positive and negative drifting branches indicates the position of the corresponding magnetic reconnection and particle acceleration site. The middle panel of Figure 3 shows an example of spike pairs that occurred around an M8.6 flare on 2005 January 15.

In the magnetic reconnection process, part of the non-potential magnetic energy is directly converted into thermal energy that heats the surrounding plasma, while another part accelerates charged particles to generate non-thermal energetic particles through reconnecting electric fields around current sheets. The energy of non-thermal electrons (E_{acc}, in keV) can be estimated from the following expression (Singh 2015; Tan et al. 2024):

$$E_{acc} \approx 1.2 \times 10^{-13} \frac{B^3}{n_e}$$

where B is the magnetic field strength (in G) near the reconnecting site and n_e is the electron density (m^{-3}). In the chromosphere, typically $n_e = 10^{17}$ m^{-3} and $B = 1000$ G, giving $E_{acc} \approx 120$ keV. In the TR, $n_e = 10^{16}$ m^{-3} and $B = 500$ G, giving $E_{acc} \approx 300$ keV. In the corona, $n_e = 10^{15}$ m^{-3} and $B = 100$ G, giving $E_{acc} \approx 120$ keV. In brief, the energy of non-thermal electrons accelerated by the reconnecting electric field may exceed 100 keV, making the electrons mildly relativistic.

These non-thermal electrons propagate perpendicular to the magnetic field, usually forming bidirectional outflow beams. The associated radio emission should be generated from GE with harmonic numbers of 10-100 and PE (fundamental and second harmonic). Similar to the discussion in Section 3.1, in the chromosphere, the related PE frequency range should be 2.8-11.4 GHz and GE should be in the range of 2.8-280 GHz. In the TR, the frequency range will be 400 MHz-5.7 GHz for PE and 1.4-140 GHz for GE (it is difficult for the actual upper limit of emission frequency to exceed 100 GHz in the chromosphere and TR). For the lower corona, typical electron density can be assumed to be 10^{15} m^{-3} and typical magnetic field strength 10-100 G. Then the associated PE will be in the frequency range of 280-560 MHz, and the associated GE will be in the frequency range of 280 MHz-5.6 GHz.

As presented in Section 2.1, it is difficult for various MHD waves generated in the photosphere to penetrate through the TR and reach the corona, so even if W heating occurs in the lower solar atmosphere, it is unlikely to occur in the corona above the TR. However, for the X mechanism, current sheets and corresponding magnetic reconnections may appear in any region with strong, magnetically frozen plasma from the upper chromosphere, TR, to the corona. The corresponding radio burst pairs will occur across a wide frequency range from 280 MHz to 280 GHz, where burst pairs in the mm-cm wavelength band likely signal X heating in the TR, while burst pairs in the dm-m wavelength band should signal X heating in the corona.

3.3. Radio Response of P Mechanisms

When the MGP mechanism (marked as P) operates in the solar atmosphere, energetic particle upflows are generated in the upper chromosphere, TR, and corona. The critical energy $\varepsilon_0(h)$ determines the lower limit of kinetic energy and velocity of the energetic particle upflow at height h. By averaging all escaping particles, the number, average velocity, and energy of the upflows can be obtained (Tan 2014). Calculations show that the averaged energy of escaping particles ranges from about 10 to 100 eV in the TR and from 100 eV to several keV in the corona (Tan 2014). The corresponding upflow velocities range from about 2000 to 1.0×10^4 km s^{-1} in the TR and (1.0-3.0) $\times 10^4$ km s^{-1} in the corona. This velocity is much higher than the local Alfvén speed (about 100-500 km s^{-1} in the TR and 500-2000 km s^{-1} in the corona) and much smaller than that of non-thermal particles accelerated by shock waves or magnetic reconnection (generally, the velocity of non-thermal particles is >0.2c, i.e., $>6.0 \times 10^4$ km s^{-1}, and the corresponding energy is >10 keV), but it is still significantly higher than the local electron thermal velocity in the TR (about 400-2000 km s^{-1}) and in the corona (2000-4000 km s^{-1}), and the Alfvén speed in the TR (about 200-600 km s^{-1}) and in the corona (600-1500 km s^{-1}).

These unidirectional energetic particle upflows are sufficient to excite Langmuir waves in plasma and generate PE in the frequency range of 2.8-11.4 GHz in the chromosphere, 400 MHz-5.7 GHz in the TR, and 280 MHz-2.8 GHz in the corona. The related radio emission will have intermediate negative frequency drifting rates that are much faster than type II radio bursts and much slower than type III radio bursts. They are somewhat similar to radio fiber bursts (Wan et al. 2021). The right panel of Figure 3 presents a group of fiber bursts that occurred far from the peak phase of an M1.9 flare.

Naturally, energetic electron upflows triggered by the MGP mechanism can also generate radio signals through CE under the action of a magnetic field, with corresponding harmonic numbers of 3-10 and frequencies of 840 MHz-28 GHz in the chromosphere, 420 MHz-14 GHz in the TR, and 100 MHz-2.8 GHz in the corona.

We know that fast-drifting radio bursts such as type III bursts and spike bursts are triggered by non-thermal high-energy electron beams with velocities >0.2c propagating in plasmas (Red & Ratcliffe 2014; Tan et al. 2019), while slow-drifting radio bursts such as type II bursts are triggered by CMEs or jets with velocities <2000 km s^{-1} (Wager & MacQueen 1983; Su et al. 2015; Hou et al. 2023). What triggers fiber bursts with intermediate frequency drifting rates? The formation mechanism of solar radio fiber bursts has not been well explained (Alissandrakis et al. 2019; Bouratzis et al. 2019). Based on the above discussions, we propose that energetic particle upflows formed by the MGP mechanism may precisely trigger the formation of fiber bursts. This may provide a more natural and reasonable explanation for the cause of solar radio fiber bursts with intermediate frequency drifting rates.

3.4. How to Observe the Radio Response Signals of Solar Atmospheric Heating?

From the above discussion, we find that due to different generation and propagation of energetic particle flows in different heating mechanisms, the spectral characteristics of excited radio emission vary greatly. These differences are summarized in Table 1. These radio emissions typically occur across a wide frequency range of 100 MHz-100 GHz (2.8-280 GHz in the chromosphere, 400 MHz-100 GHz in the TR, and 100 MHz-28 GHz in the corona). The frequencies corresponding to different emission mechanisms also vary slightly. To verify heating mechanisms in different solar atmospheric regions, we need dynamic spectral observations across a wide frequency range of 100 MHz-100 GHz, covering meter wave, decimeter wave, centimeter wave, to millimeter wave bands. If we can observe different solar regions (AR, QR, CH, or polar region) using ultra-wideband radio spectrometers and extract spectral parameters (including frequency bandwidth, lifetime, frequency drifting rate, polarization degree, repetition rate, and group distribution), it may be possible to identify and verify their heating mechanisms.

We also found that the frequency of solar atmospheric heated non-thermal radio emission is related not only to atmospheric layers (chromosphere, TR, or corona) but also to the emission mechanism, which may result in radio response signals from different layers appearing in the same frequency range. How can we distinguish them? We know that the frequency of coherent PE is:

$$f = s\sqrt{\frac{n_e e^2}{\pi m_e}} \approx 9\sqrt{n_e}$$

where $s = 1$ is the fundamental plasma emission and $s = 2$ is the second harmonic plasma emission. The corresponding frequency drifting rate is:

$$\frac{df}{dt} = \frac{df}{dn_e}\frac{dn_e}{dr}\frac{dr}{dt} = \frac{df}{dn_e}\frac{dn_e}{dr}v_e$$

where v_e is the velocity of energetic electrons. From Figure 2, we see that in both the chromosphere and corona, electron number density decreases slowly, and its gradient is relatively small, while in the TR, density decreases rapidly and its gradient is very large. This indicates that the frequency drifting rate of non-thermal radio emission occurring in the chromosphere and corona is relatively small, while the frequency drifting rate in the TR is very high. This can serve as an important criterion for distinguishing non-thermal radio signals from the chromosphere, TR, and corona.

For incoherent CE (low-energy upflow electrons produced by the P mechanism) and GE (mildly relativistic electrons produced by W and X mechanisms), $f = sf_{ce}$, where f_{ce} is the electron gyrofrequency and s is the harmonic number. The related frequency drifting rate is proportional to the magnetic gradient: $\frac{df}{dt} \propto \frac{dB}{dr}$. Similar to density change characteristics, the magnetic field in the chromosphere and corona gradually decreases with a small gradient, while in the TR it rapidly decreases with the highest gradient. This characteristic determines that the frequency drifting rate is relatively small in the chromosphere and corona, and highest in the TR.

Radio emissions with frequencies below 15 GHz are completely transparent to Earth' s atmosphere and can be directly observed using ground-based solar radio telescopes. However, unlike radio telescopes specifically designed to observe solar eruptive activities (such as flares and CMEs), the observation targets here are mainly non-thermal emission signals during quiet Sun conditions, including spike groups, spike pairs or type III pairs, fiber groups, etc. These require telescopes with very high sensitivity and high temporal and frequency resolution, which are difficult for general radio telescopes to accurately detect. Only large-aperture telescopes or telescope arrays composed of multiple elements can detect these signals, such as MUSER (40/60 dishes, 400 MHz-15.0 GHz, covering the upper TR to corona and very suitable for detecting radio bursts from ARs, Yan et al. 2021), FAST Core Array (0.35-10.0 GHz, covering the upper TR to corona with very high sensitivity and spatial resolution, very suitable for detecting weak signals from quiet Sun and ARs, Jiang et al. 2024), and the future SKA.

Due to strong absorption by oxygen and water molecules in Earth' s atmosphere, no existing telescope can obtain broadband dynamic spectrum observations in the frequency range of 15-100 GHz. Currently, broadband dynamic spectrum observations in this frequency range remain blank both domestically and internationally. Therefore, to identify and verify different heating mechanisms in the solar atmosphere, we propose implementing a radio exploration plan for chromospheric and TR heating mechanisms through three steps. The first step is to select frequency bands with weaker atmospheric absorption and develop new broadband dynamic spectrometers in dry, high-altitude locations, such as the Solar Ultra-Broadband Millimeter-wave Spectrometers (SUBMS) currently under development at Lenghu Station in Qinghai Province, with an observation frequency range of 15-36 GHz (Tan et al. 2024). SUBMS may provide information on non-thermal heating processes in the upper TR. After this step is successfully implemented, we will consider the second step: mounting radio dynamic spectrometers on a space platform to observe the full frequency range (15-100 GHz, covering the chromosphere and TR) from outside Earth' s atmosphere. This step will obtain clean broadband dynamic spectra with high temporal and spectral resolution. When the second step is also successful, we will consider the third step: building a millimeter-wave telescope array on a platform such as the Chinese Space Station and using the synthetic aperture principle to carry out broadband dynamic spectral imaging observations, detecting heating signals in the solar atmosphere above ARs, QRs, CHs, and polar regions.

Through joint observations from ground-based and space telescopes across the frequency range from millimeter to meter waves, we may obtain complete information on heating processes from the solar chromosphere, TR to the corona, providing observational evidence for solving the mystery of coronal heating.

4. Conclusion

Coronal heating is a very difficult and complicated problem. Based on the above discussions, we obtained the following conclusions:

1. It is likely that multiple heating mechanisms (W, X, and P heating mechanisms) work together in the solar atmosphere, with different contributions from the chromosphere to the TR to the corona. The W mechanism may dominate heating in the chromosphere and lower TR, while the P mechanism may dominate heating in the TR and corona, and X heating likely provides only a small contribution to heating the solar atmosphere. Spicules and small-scale jets, which have been widely discussed in recent years, are partly related to X heating, partly related to W heating, and partly formed by P processes.

2. Among these heating mechanisms, the generation and propagation characteristics of non-thermal energetic electrons differ. They produce different spectral structural features in broadband dynamic radio spectra: W heating manifests mainly as RDSG, X heating manifests as type III burst pairs or spike pairs, and the P mechanism manifests as fiber burst groups. Possible related emission mechanisms include coherent PE, incoherent CE (low-energy upflow electrons produced by the P mechanism), and GE (mildly relativistic electrons produced by W or X mechanisms). For each type of radio burst, when it originates from the chromosphere, the frequency drifting rate should generally be relatively slow in the high-frequency range (2.8-280 GHz); when from the TR, the frequency drifting rate should be relatively high in the moderate-frequency range (1.4-140 GHz); and when from the corona, the frequency drifting rate should be-

come relatively slow in the frequency range (100 MHz–5.6 GHz). Different emission mechanisms related to heating processes also produce different spectral features of radio bursts, including frequency bandwidth, lifetime, frequency drifting rate, polarization degree, etc. It is possible to identify and verify heating mechanisms at different atmospheric layers through observations of radio ultra-wide dynamic spectra during quiet Sun conditions.

3. The non-thermal radio emissions related to solar atmospheric heating mechanisms span an ultra-broadband frequency range from meter waves (down to 100 MHz) to millimeter waves (up to >100 GHz), requiring observations with high sensitivity, high temporal resolution, high frequency resolution, and simultaneous spectral and imaging capabilities during quiet Sun periods, without the effects of powerful solar eruptions.

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