Postprint of Electron Cyclotron Maser Radiation in Solar Radio Burst Phenomena

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Abstract

Solar radio bursts (SRB) are induced radiation phenomena arising from the interaction between solar energetic electrons and background plasma. Their diverse dynamic spectral types and complex fine structures reflect rich physical information regarding the magnetic plasma configuration in the source region, while the underlying radiation mechanisms serve as crucial tools for deciphering such information. For a long time, two primary mechanisms have remained controversial in SRB radiation studies: the plasma radiation mechanism and the electron cyclotron maser (ECM) radiation mechanism. In recent years, novel ECM-driven models have been developed to address major difficulties encountered when applying traditional ECM mechanisms to SRB phenomena. These models incorporate driving by low-energy cutoffs in power-law electron spectra and the effects of self-generated Alfvén waves from fast electron beams, and have been successfully applied to explain the formation mechanisms of various SRB dynamic spectra. Based on these new ECM radiation models, the applications of the ECM radiation mechanism across different types of SRB phenomena have been systematically summarized, providing a consistent and unified physical interpretation for the formation of their distinct dynamic spectral structures.

Full Text

Preamble

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Electron Cyclotron Maser Emission in Solar Radio Bursts

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Abstract

Solar radio bursts (SRBs) are induced radiation phenomena produced by the interaction between solar energetic electrons and background plasma. Their diverse dynamic spectral types and complex fine structures reflect rich physical information about the magnetic-plasma structural state in the radiation source region, and the relevant radiation mechanisms serve as key tools for interpreting this physical information. For a long time, two competing mechanisms have dominated SRB radiation mechanism research: the plasma radiation mechanism and the electron cyclotron maser (ECM) radiation mechanism. In recent years, to address major difficulties encountered when applying traditional ECM radiation mechanisms to SRB phenomena, new ECM-driven models have been developed that are powered by low-energy cutoffs in power-law electron spectra and incorporate the effects of self-generated Alfvén waves from fast electron beams. These models have been successfully applied to explain the formation mechanisms of various SRB dynamic spectra. Based on these new ECM radiation models, this paper systematically summarizes the application of ECM radiation mechanisms in different types of SRB phenomena and provides a consistent, unified physical interpretation for the formation of their different dynamic spectral structures.

Keywords: radiation mechanisms: non-thermal, Sun: activity, Sun: magnetic fields, Sun: radio radiation

Classification Codes: P144; Document Code: A

Solar radio burst radiation primarily originates from the Sun's outer atmosphere and is closely related to solar activity. It is an induced radiation phenomenon excited by high-energy electrons generated during solar activity processes within the solar atmospheric plasma. Consequently, the radiation frequency depends on the intrinsic frequencies of the local plasma, such as the electron Langmuir frequency or electron cyclotron frequency. It is generally believed that both plasma density and magnetic field strength in the solar atmosphere decrease with increasing heliocentric distance. Therefore, the characteristic frequencies of SRBs also decrease with increasing altitude in the solar atmosphere. As a result, different waveband SRBs originate from different regions of the solar atmosphere: higher-frequency radiation comes from lower atmospheric layers, while lower-frequency radiation originates from higher layers. Due to technical limitations, early SRB observations were mostly concentrated in the meter-wave band, with frequency ranges from tens to hundreds of MHz, typically corresponding to coronal regions above 100,000 km. With the continuous expansion of observational wavebands, SRB observations now extend to GHz frequencies (centimeter and millimeter waves) at the high-frequency end, known as microwave bursts. Space satellite observations have also overcome the Earth's ionospheric cutoff frequency (approximately 10 MHz) limitation, extending observations to the kHz band (kilometer waves) at the low-frequency end.

Traditional Type I to V SRBs mainly refer to meter-wave bursts from the high corona. Microwave bursts mostly originate from the low corona below 100,000 km, where the solar plasma atmosphere has more complex magnetic field structures, causing microwave bursts to exhibit more complex dynamic spectral structures [1]. For SRB phenomena observed below 10 MHz by satellites in outer space, there are generally two possible origins: first, they may directly originate from interplanetary space as local interplanetary radio bursts, which can be considered an extension of solar eruptive activities into interplanetary space—i.e., high-energy electron beams produced by solar eruptive activities propagate into interplanetary space and excite local interplanetary radio bursts; second, their direct source region may also be within low-density cavity ducts in the outer corona, which then propagate outward through the low-density ducts to interplanetary space until observed by satellites, also known as interplanetary SRBs.

The goal of scientific research is to explain as many complex phenomena as possible with the simplest universal principles or theoretical models. Compared with plasma radiation mechanisms based on nonlinear wave-wave coupling processes of Langmuir waves, the ECM radiation mechanism based on linear electron cyclotron maser instability is obviously simpler and clearer in physical principle. Electron Cyclotron Maser Emission (ECME) is a radiation process where non-thermal electrons directly amplify electromagnetic waves near the electron cyclotron frequency or its harmonics through wave-particle interactions. Since its proposal in the 1950s, it had not been well developed due to the limitations of non-relativistic resonance conditions. Until 1979, Wu et al. [2] considered the weak relativistic effect of electron mass in the wave-particle resonance condition and simultaneously considered the magnetic mirror effect in Earth's magnetosphere, proposing that high-energy electrons have a loss-cone distribution and successfully explaining some observational characteristics of Auroral Kilometric Radiation (AKR) using ECM radiation. The Wu-Lee model proposed two assumptions: first, regarding the electron velocity space distribution, it was assumed that non-thermal electrons have a loss-cone distribution due to magnetic mirror effects; second, regarding the plasma density and magnetic field strength in the source region, it required a strong magnetic field and low density, i.e., the electron cyclotron frequency must be greater than the local plasma frequency. These two assumptions constitute the ECM radiation hypotheses about the free energy source and radiation escape. High-energy electrons produced in astrophysical activities generally have quasi-parallel directions when leaving the acceleration region, meaning they propagate roughly along the magnetic field direction, thus lacking sufficient free energy in the direction perpendicular to the magnetic field. Additionally, for most solar atmospheric plasma environments, the plasma frequency is often greater than the electron cyclotron frequency. Therefore, when applying ECM radiation to solar radio bursts, these two difficulties must first be resolved.

Research shows that Alfvén waves, due to their non-dissipative nature, are ubiquitous in the solar atmosphere and solar wind plasma and become the dominant low-frequency electromagnetic disturbance. Alfvén waves are also easily excited, and many types of free energy in solar atmospheric plasma can excite Alfvén waves, such as high-energy particle beams [3–4], field-aligned currents [5–6], temperature anisotropy, and velocity shear in plasmas [7]. Using ω and k = (k__x; 0; k__z) to denote the wave frequency and wave vector (with background magnetic field along the solar radial z-direction), the basic characteristics of waves are determined by the dispersion relation. The Alfvén wave dispersion relation is ω = v__A k cos = v__A k__z, where v__A represents the Alfvén wave velocity and is the angle between the wave vector and background magnetic field. The phase velocity of Alfvén waves is v__A cos , which depends only on the wave propagation direction and not on frequency, meaning Alfvén waves are non-dispersive. The group velocity v__g = ω/ k = v__A i__z, where i__z is the unit vector in the z-direction. Thus, the group velocity direction is along the magnetic field, with magnitude equal to the local Alfvén wave velocity, meaning Alfvén waves propagate energy along magnetic field lines.

The perturbation fields of Alfvén waves affect the motion state of high-energy electrons in field-aligned fast electron beams, primarily in two aspects. First, they affect the "unperturbed orbits" of field-aligned fast electrons, where the unperturbed orbits are no longer standard Larmor gyration orbits but modified orbits influenced by Alfvén wave turbulence. Second, through pitch-angle scattering of fast electrons by the Alfvén wave field, the original velocity distribution state of the field-aligned electron beam is altered. Field-aligned fast electron beams are considered the excitation source driving solar radio bursts, so changes in their motion state consequently affect the ECM radiation they excite.

Wu et al. [8] and Chen et al. [9] proposed a self-consistent ECM radiation model that considers the influence of Alfvén waves excited by the current instability of high-energy electron beams on their ECM radiation. Similar to background Alfvén wave perturbations, self-generated Alfvén waves also have important effects on ECM radiation excited by high-energy electron beams: first, they can change the polarization state of ECM radiation. Since self-generated Alfvén waves cause field-aligned oscillating currents in electron beams that directly excite O-mode radiation, the growth rate of O-mode radiation increases significantly and becomes the dominant radiation; second, they provide additional free energy for ECM radiation. Due to the pitch-angle scattering effect of self-generated Alfvén waves, the field-aligned kinetic energy of high-energy electron beams is directly converted into perpendicular kinetic energy, changing their velocity distribution from a beam distribution to a shell distribution; third, they create escape conditions for ECM excitation. Under the pressure of self-generated Alfvén waves, background plasma is displaced along the propagation path of high-energy electron beams, forming a low-density cavity duct. Within this duct, the condition that plasma frequency is less than electron cyclotron frequency is easily satisfied. In summary, the self-consistent ECM radiation model proposed by Wu et al. [8] includes the following key points:

(1) High-energy electrons propagate along the background magnetic field, generating enhanced Alfvén wave turbulence due to current instability, i.e., self-generated Alfvén waves;

(2) Beam electrons form field-aligned oscillating currents under the influence of self-generated and background Alfvén waves, which can directly excite O-mode radiation and significantly increase the O-mode growth rate without affecting the X-mode growth rate, thus transforming the polarization state of ECM radiation from X-mode dominance to O-mode dominance;

(3) Similarly, under the pitch-angle scattering effect of self-generated and background Alfvén waves, the velocity distribution of high-energy electron beams is altered, converting the field-aligned kinetic energy of high-energy electrons into perpendicular kinetic energy and providing additional free energy for ECM radiation;

(4) Additionally, under the pressure of self-generated Alfvén waves, background plasma is displaced along the propagation path of high-energy electron beams, forming a low-density cavity duct. Within the duct, the escape condition for ECM radiation is easily satisfied, i.e., the plasma frequency inside the low-density duct is significantly less than the electron cyclotron frequency.

The main advantage of this self-consistent ECM model is that the effects of self-generated Alfvén waves on ECM radiation can effectively overcome the major difficulties encountered when applying traditional ECM radiation to solar radio bursts, namely "escape, excitation, and polarization" problems. Based on our new understanding of the complex magnetic-plasma structure of the solar atmosphere [10] and recent progress in ECM radiation mechanism research [8–9, 11–12], these difficulties of traditional ECM radiation can all be reasonably explained. As Wu Jingsheng pointed out: "It is time to re-examine the theoretical models of SRBs, particularly the possible application of ECM radiation mechanisms in SRB phenomena [13]." Based on these considerations, we have recently re-examined the application of new ECM radiation mechanisms in various traditional SRB phenomena from Type I to Type V, attempting to provide a self-consistent and reasonable unified explanation for different types of complex SRB phenomena using the single physical principle of ECM radiation, where all types of bursts are excited by the ECM mechanism, while the formation of different dynamic spectral types is attributed to different magnetic-plasma environments in the radiation source regions.

2 Model Parameters of the ECM Radiation Mechanism and Observable Quantities of Solar Radio Bursts

To enable effective comparison and verification between theoretical models and observational phenomena, it is crucial to establish necessary direct connections between the physical parameters of theoretical models and the measurable parameters of observational phenomena. The model parameters of the new self-consistent ECM radiation mechanism are relatively complex, involving two major categories: background plasma parameters and high-energy electron beam parameters. Background plasma parameters can be further divided into static parameters describing the static environment of background plasma (such as background plasma density, temperature, magnetic field, and derived parameters like thermal-to-magnetic pressure ratio, magnetic mirror ratio, Alfvén velocity, etc.) and perturbation parameters describing the perturbed environment of background plasma (such as the relative intensity of background turbulent Alfvén waves). High-energy electron beam parameters can also be divided into two categories: energy spectrum parameters describing the non-thermal characteristics of the electron energy distribution (such as the power-law index in the high-energy segment, the spectral steepening index in the low-energy segment, and the transition cutoff energy between high and low energy segments) and velocity distribution parameters describing velocity anisotropy characteristics (such as loss-cone parameters, ring peak velocity or peak pitch angle, and various velocity dispersions or pitch-angle broadenings).

From the growth rate expressions for ECM radiation excitation [14–15], it is evident that all the above model parameters can significantly affect the final calculation results of specific models. For example, although the fundamental wave escape condition for ECM radiation requires the escape parameter $\omega\{ce\}/\omega\{\mathrm{pe}\} > 1$ (where $\omega\{ce\}\ and\ \omega\{\mathrm{pe}\}$ are the electron cyclotron frequency and plasma frequency, respectively), excessively high escape parameters are not always conducive to effective radiation excitation, depending on the specific model chosen, particularly the specific form of the high-energy electron beam velocity distribution function. Numerical calculations using the model in reference [14] show that when the escape parameter $\omega\{ce\}/\omega\{\mathrm{pe}\} > 10$, the growth rates of almost all wave modes approach zero, meaning ECM radiation excitation is completely suppressed. In the range $10 > \omega\{ce\}/\omega\{\mathrm{pe}\} > 3$, the growth rate of the X1 mode exceeds that of the O1 mode, making it the dominant fundamental wave polarization mode. However, in the range $3 > \omega\{ce\}/\omega\{\mathrm{pe}\} > 1$, the fundamental X1 mode is suppressed because it cannot escape, so the fundamental polarization is dominated by O1. When the escape parameter decreases to the range $1 > \omega\{ce\}/\omega\{\mathrm{pe}\} > 3/4$, all fundamental waves are suppressed, and the dominant radiation mode becomes X2. When $1/2 < \omega\{ce\}/\omega\{\mathrm{pe}\} < 3/4$, the X2 mode is also suppressed, and the O2 mode begins to dominate. When $\omega\{ce\}/\omega\{\mathrm{pe}\} < 1/2$, harmonics below the second order are all suppressed, and only higher-order harmonic radiation may escape. These numerical results demonstrate the sensitivity of the model to parameters, and similar situations exist for changes in other model parameters. This should be a general characteristic of ECM radiation mechanisms, and calculations in references [16–17] show similar results.

On the other hand, from an observational perspective, the measurable parameters of SRBs can be divided into two categories: state parameters and spectral parameters. The former includes burst radiation peak flux, radiation brightness temperature, polarization state and degree, radiation lifetime, etc., while the latter includes burst radiation peak frequency, radiation bandwidth, peak frequency drift rate, radiation spectrum and its fine structures, etc. However, there is no simple correspondence between these observational parameters and model parameters. Typically, one observational parameter may be simultaneously affected by several model parameters, and likewise, one model parameter may simultaneously affect the measured values of multiple observational parameters. Moreover, both the determination of background plasma parameters and the measurement of radio burst radiation parameters currently have considerable uncertainties given observational technology limitations. For example, measurements of basic parameters like background plasma density and magnetic field in the coronal environment have large uncertainties, with differences of several times or even orders of magnitude being within possible measurement estimation error ranges. Therefore, when applying theoretical models to explain observational phenomena, comprehensive analysis must be conducted for specific observational phenomena and background plasma environmental conditions, and maintaining theoretical model self-consistency in analytical applications becomes particularly important.

Solar radio broadband observations are considered the most important means for diagnosing magnetic fields (in the corona and high chromosphere) and plasma parameters. Solar radio radiation spans more than five orders of magnitude in frequency, from sub-millimeter waves to hectometer waves, with radiation source regions located from the low chromosphere to the extremely high corona and even interplanetary space, including quiet solar regions, active regions, and flare burst source regions. These radio radiation sources include dense, partially ionized chromospheric plasma, fully ionized coronal plasma, and high-energy electrons, with different excitation sources having different radiation mechanisms. Therefore, different radio radiation mechanisms dominate in different regions of the solar atmosphere. Through measurement of these observational parameters, we can identify the radiation mechanisms in the source region and potentially establish definitive diagnostic methods for coronal magnetic fields and plasma parameters through the physical relationships between these parameters and magnetic/plasma parameters. For Alfvén wave-modulated ECM radiation, it is likely the generation mechanism for certain solar radio fine structures, such as Type IIIb [18–19], and Alfvén wave-related parameters (such as Alfvén wave intensity, frequency, and Alfvén velocity) may be closely related to certain observational characteristics of these fine structures (such as stripe spacing and stripe frequency drift rate). Currently, there are few studies using ECM radiation to diagnose magnetic fields and plasma parameters, while ECM radiation is being increasingly widely applied in solar radio bursts. Therefore, in subsequent research, it is highly necessary to utilize ECM radiation, especially Alfvén wave-modulated ECM radiation, for diagnostic studies of magnetic fields and other related parameters.

3 ECM Radiation from Electrons Trapped in Coronal Loops and Type I SRB Phenomena

The earliest observed SRBs [20] belonged to Type I bursts, which are also the only type of SRB not directly associated with intense eruptive activities such as solar flares or coronal mass ejections, though they are sometimes related to the triggering of coronal mass ejections [21]. They typically occur in large sunspot regions and accompany large-scale changes in coronal magnetic field structures, which are mostly related to emerging magnetic flux with emergence timescales of several hours to days [22–26]. In spectrograms, they generally appear as broadband continuous spectrum radiation lasting several hours to days (relative bandwidth: $\Delta f/f$ 100%), along with a series of short-duration (0.1–1 s) narrowband ($\Delta f/f$ 3%) spike bursts superimposed on the continuous spectrum. The continuous spectrum radiation source has a size of several arcminutes and brightness temperatures between 10^7–10^{10} K, while spike bursts have source sizes of about one arcminute and brightness temperatures exceeding 10^{11} K [27].

The most unique feature of Type I SRB dynamic spectra is the frequent display of nearly 100% O-mode polarization [28]. Therefore, the primary task of Type I SRB models is to explain this prominent O-mode polarization characteristic. In early studies of Type I SRB radiation mechanisms, the ECM radiation mechanism was also suggested [29–30]. However, Melrose [31] found that the X2 mode in ECM radiation mechanisms could grow even faster than the O1 mode, establishing that ECM radiation mechanisms are generally dominated by the extraordinary mode. Based on this, Melrose [32] further clearly pointed out that Type I SRBs should be produced by plasma radiation mechanisms [33]. Since then, the plasma radiation mechanism has been widely accepted as the main generation mechanism for Type I SRB phenomena.

Based on the observational fact that Type I SRBs are produced in strong magnetic field regions undergoing large-scale structural evolution, Zhao et al. [34] re-examined the possibility that Type I SRBs are generated by ECM radiation mechanisms. When large-scale magnetic field structure evolution such as magnetic flux rope emergence occurs, it is usually accompanied by large-scale current activity, implying that the background plasma environment may have strong Alfvén wave perturbations that strongly affect the motion state of high-energy electrons trapped in closed magnetic loops above sunspots, forming field-aligned oscillating currents and pitch-angle distribution broadening, thereby significantly affecting the polarization state changes of ECM radiation from these high-energy electrons. Further considering the loss-cone velocity distribution caused by the magnetic mirror effect of closed loops and the non-thermal power-law spectral characteristics of high-energy electron energy distributions

[15, 35], Zhao et al. [34] adopted the following distribution function to describe the high-energy electron distribution trapped in closed magnetic loops above sunspots:

F_b(u;) = A_b H( ) [1 - exp[(1 - σ)(1 - ^{2})/Δ ^{2}]] u^{-α} $\times$ {1 + (u^2/u_c^2)$^{\{\delta/2\}}$}{-1}

where A_b is the normalization coefficient, H( ) is the Heaviside step function, σ is the magnetic mirror ratio, = u_ /u and Δ (i.e., δ) are the pitch angle (ratio of velocity parallel to background magnetic field to total velocity) and its dispersion of trapped electrons, respectively, u_c = √(2E_c/m_e), α, δ, and E_c are the power-law index in the high-energy segment, the spectral steepening index in the low-energy segment, and the transition cutoff energy (or peak energy) between high and low energy segments of the non-thermal energy spectrum of trapped electrons. For given parameters: $\alpha = 3$, $\delta = 6$, $\sigma = 10$, $\Delta = 0.9$, and E_c = 20 keV, the variation of maximum growth rates of different radiation wave modes excited by the ECM radiation mechanism from trapped electrons with the turbulence level of Alfvén waves in the background magnetic loop (δB^2/B$_0$^{2}, i.e., , where B_w and B$_0$ represent Alfvén wave magnetic field and background magnetic field intensity, respectively) is shown in Figure 1 [Figure 1: see original paper]. Here, $\Omega = \omega${pe}/ω{ce} is the plasma parameter, and the maximum growth rate γ{max} *is normalized by the electron cyclotron frequency Ω_e (i.e.,* ω{ce}) and density ratio n_b/n$_0$. The results clearly show that as long as the turbulent Alfvén wave intensity δB^2/B$_0$^{2} > 0.005, the polarization state of the corresponding ECM radiation is dominated by the O1 mode, meaning that the observed Type I SRBs exhibit O-mode polarization.

Figure 2 [Figure 2: see original paper] shows the variation of the O1 mode radiation frequency ω{ce} *(upper panel) and plasma parameter* ω{pe}/ω{ce} *(lower panel) with coronal height (in units of solar radius R*), where solid and dashed lines are calculated based on sunspot magnetic field models from references [36–37] and the Baumbach-Allen model [38] for electron density height distribution, respectively. From Figure 2, it is evident that below heights of 0.5 R_ , the O1 mode radiation escape condition ω{pe}/ω{ce} < 1 is well satisfied, with corresponding O1 mode radiation frequencies ranging from tens of MHz at 0.5 R_ to hundreds of MHz below 0.2 R_ . On the other hand, observations show that the frequency range of Type I SRBs is indeed between 50–500 MHz, particularly with the height distribution of radiation frequency basically falling within the range shown in the figure. For example, the source heights of Type I SRBs at frequencies of 200 MHz, 97 MHz, and 77 MHz (shown as horizontal dotted lines in the figure) are approximately 0.2–0.3 R_ [39], 0.3–0.4 R_ [28], and 0.32 R_ [40], respectively.

Regarding the relationship between narrowband spike bursts frequently superimposed on Type I SRB continuous spectrum radiation and the continuous spectrum radiation itself, Zhao et al. [34] made the following speculation: as current-carrying magnetic flux tubes emerging from beneath the photosphere rise, they interact with the original sunspot magnetic field, forming local coronal currents on one hand and continuously releasing energy through small-scale magnetic reconnection processes on the other. These small-scale magnetic reconnections occur intermittently and continuously throughout the entire rising process of the emerging flux tube, continuously producing a series of small-scale high-energy electron beams. Some of these beams continuously enter sunspot magnetic fields and become trapped in closed magnetic loops, serving as the excitation source for Type I SRB continuous spectrum radiation, while others may enter open magnetic fields near the reconnection region and escape, producing the narrowband spike bursts in Type I SRBs [41]. Therefore, the duration of broadband continuous spectrum radiation corresponds to the entire emergence and rising process of the current-carrying magnetic flux tube (several hours to days), the bandwidth depends on the magnetic field variation range of the closed magnetic loop, while the duration of narrowband spike bursts depends on the lifetime of individual high-energy electron beams produced by single small-scale magnetic reconnections (0.1–1 s), and the bandwidth is determined by the coherent characteristics of individual electron beams.

In this new physical picture, two main observational features closely related to the source region environment of Type I SRBs can be well explained: strong magnetic fields satisfy the O1 mode escape condition for ECM radiation, while magnetic flux emergence (i.e., large-scale magnetic activity, or current activity) leads to enhanced turbulent Alfvén wave activity that changes the polarization state of ECM radiation to be dominated by O-mode (actually O1 mode), producing strongly polarized O-mode radiation. However, the physical essence behind this new physical picture is actually the macroscopic and microscopic dynamic processes of formation and evolution of local coronal plasma current systems accompanying large-scale magnetic flux emergence, which still requires further in-depth and detailed research.

4 ECM Radiation from Shock-Accelerated Electrons along Open Field Lines and Type II SRB Phenomena

Unlike the strong polarization characteristics of Type I SRBs, most Type II SRBs are unpolarized, with only a few cases showing very weak polarization. The first SRB observed to have possible frequency drift phenomena was a Type II burst [42], whose most significant spectral feature is the slow frequency drift from high to low frequencies at a relatively low rate (1 MHz/s), with typical instantaneous bandwidths from several MHz to about 100 MHz and durations of approximately 5–15 minutes [43]. Type II SRBs also have the richest spectral structure features among all SRB phenomena. Numerous observational studies have found that about 60% of Type II SRB events exhibit fundamental-harmonic pair structures, with the corresponding harmonic-to-fundamental frequency ratio slightly less than 2. Moreover, the fundamental and harmonic frequency bands occasionally exhibit so-called "band-splitting" phenomena, where the fundamental and harmonic each further split to form double-band structures separated by approximately Δf   0.1f [44]. Additionally, the main frequency band of Type II SRBs sometimes shows a "backbone" structure superimposed with a series of "herringbones," forming a "backbone-herringbone" structure [45].

The relatively low frequency drift from high to low frequencies in Type II SRBs implies a relatively slow outward motion speed of the radiation excitation source. Based on empirical models of the solar atmosphere, the corresponding characteristic motion speeds are estimated to be on the order of hundreds to thousands of kilometers per second, i.e., typical magnetohydrodynamic wave speeds. Moreover, observations show they have clear statistical correlations with coronal mass ejections and their driven shocks, so Type II SRBs are generally believed to be produced by electrons accelerated by coronal mass ejection-driven shocks [44, 46]. Shock acceleration, as an effective acceleration mechanism for high-energy particles in cosmic astrophysics, has been widely studied in astrophysical and space physics fields and is one of the most important high-energy particle acceleration mechanisms in high-energy astrophysics [47]. The typical physical picture in traditional Type II SRB radiation theory is as follows: during the outward propagation of a shock wave driven by a coronal mass ejection, high-energy electrons with energies of several keV or more are continuously produced through shock acceleration mechanisms. These shock-accelerated high-energy electrons excite Langmuir waves through plasma instability, which are then converted into radio wave radiation at the local plasma frequency or its second harmonic through standard plasma radiation mechanisms via nonlinear wave-wave coupling [27]. However, Lobzin et al. [48] pointed out that shock acceleration processes or turbulent acceleration processes generally more easily form "ring-beam" or "loss-cone" type velocity distributions of high-energy electrons, thus more likely leading to ECM radiation rather than plasma radiation excitation.

In the model further proposed by Yoon et al. [49], ring-beam high-energy electrons produced by quasi-perpendicular shock acceleration drive ECM instability and directly excite the backbone radiation of Type II SRBs, while herringbone radiation may be produced by high-energy electrons reflected by the shock into upstream regions entering higher and lower magnetic field areas.

The greatest challenge for Type II SRB theoretical models is how to self-consistently and reasonably explain a series of distinct structural features including "slow frequency drift, no polarization, fundamental-harmonic pairs, backbone-herringbone, band-splitting" within a unified model framework. Considering the influence of self-generated Alfvén waves from shock-accelerated particles, Zhao et al. further proposed a new ECM radiation model caused by shock-accelerated electrons. The basic physical picture is shown in Figure 3 [Figure 3: see original paper] [50]: consider a shock wave propagating outward from the corona. Near the quasi-perpendicular propagation region (where the angle between the shock surface normal and magnetic field is greater than 45°), high-energy electron beams and ion beams accelerated by the shock form a so-called "foreshock" region, with boundaries shown by dashed lines in the figure. Then, enhanced self-generated Alfvén waves excited by the current instability of these beams form a low-density cavity (blue region in the figure) along the foreshock region boundary. Simultaneously, due to the pitch-angle scattering effect of self-generated Alfvén waves, shock-accelerated electrons with ring-beam distributions within this low-density cavity will form high-energy electron beams with shell distributions, which then effectively excite ECM radiation at fundamental and harmonic frequencies through ECM instability. Due to cutoff reflection effects outside the low-density cavity, initially excited ECM radiation will be confined within the low-density cavity, propagate along the foreshock boundary, and be continuously reflected until the initially excited frequency exceeds the external cutoff frequency and escapes.

Based on the above basic physical picture, we believe the main observational characteristics of Type II SRBs can be explained as follows:

(1) The non-polarized (or weakly polarized) characteristics of Type II SRBs are mainly the result of initially generated polarized radiation being confined within the low-density cavity and experiencing multiple reflections and merging, gradually reducing the degree of polarization. Since the polarization state of radiation is directly affected by the angle between the radiation propagation direction and the magnetic field, and the angle changes with each reflection of the radiation wave, the polarization state changes. The merging with incident radiation waves leads to reduced polarization;

(2) Regarding the backbone-herringbone structure of Type II SRBs, we believe there is actually no independent "backbone" radiation, only a series of "herringbone" radiations. The so-called backbone radiation is simply formed by the superposition and coincidence of a series of herringbone radiations. That is, shock acceleration continuously produces high-energy electron beams ejected along the foreshock boundary, and each high-energy electron beam excites ECM radiation that constitutes a "herringbone" radiation (essentially a small-scale Type III SRB). Whether resolvable "herringbone" structures can be observed in a specific event depends on the "production rate" of electron beams in the shock acceleration mechanism and the shock propagation speed;

(3) There are two possible reasons for band-splitting formation. One is that ripple fluctuations of the shock surface cause local tilting of the shock surface and reflection of electron beams, resulting in bidirectional beam distributions of high-energy electrons and double-peak characteristics of excited ECM radiation growth rates that create double-band structures. The other is that unequal magnetic field strengths on both sides of a curved shock surface lead to band-splitting phenomena [51];

(4) Regarding the fundamental-harmonic structure, there is also a puzzling observational phenomenon: the observed source regions of fundamental and harmonic waves with the same frequency sometimes appear at the same height [44]. This can also be reasonably explained under the current scenario where initially excited radiation is confined within a low-density

cavity, because the current observed source region is not their initial radiation source region but rather the "apparent source region" where the initially excited frequency exceeds the plasma cutoff frequency outside the cavity. Therefore, it is entirely determined by the magnitude of the initially excited frequency and is independent of the excitation mode;

(5) Additionally, in plasma radiation mechanisms, the frequency drift of SRBs depends on the gradient of plasma density changes along the radiation source region's motion path, whereas in ECM radiation mechanisms, the corresponding frequency drift depends on the gradient of magnetic field strength changes along the source region path. Combining empirical models of solar atmospheric density and magnetic fields, the shock propagation speed can be obtained from the frequency drift of Type II SRBs. However, based on plasma radiation mechanisms and atmospheric density models, the frequency drift of some Type II SRB events yields shock propagation speeds that may reach abnormally high values even exceeding 10^4 km/s [52], since typical magnetohydrodynamic wave propagation speeds in the solar atmosphere are generally in the range of hundreds to thousands of km/s. On the other hand, based on ECM radiation mechanisms and atmospheric magnetic field models, the "ultra-high-speed" shock sources of these Type II SRBs can be reduced to about 3×10^3 km/s [50], which should be a more reasonable fast shock speed.

5 ECM Radiation from Reconnection-Accelerated Electrons along Open Field Lines and Type III SRB Phenomena

Type III bursts are the SRB phenomenon most directly associated with solar flares, especially their connection with hard X-ray flares. Just as AKR and Earth's aurora are twin brothers of geomagnetic substorms, Type III bursts and solar flares are also twin brothers [53]. Due to this direct connection with solar flares, Type III bursts are also the most powerful, most frequently observed, and most extensively studied class of SRBs [54–57]. Generally, Type III bursts appear in groups, with each group containing several to dozens of individual bursts lasting several seconds to tens of seconds, with frequency ranges extending from several GHz in the microwave band to about 10 kHz in interplanetary space. The most important spectral characteristic of Type III bursts is rapid frequency drift, with drift rates decreasing as frequency decreases [58]. The rapid frequency drift of Type III bursts implies that their radiation sources are sub-relativistic high-energy electron beams with motion speeds as high as 10^5 km/s (0.3c, where c is the speed of light) and energies of about 50 keV, which is also the first direct observational evidence of high-energy fast electron beam propagation in the solar atmosphere [59]. Similar to Type II bursts, Type III bursts also have harmonic structures, with harmonic-to-fundamental frequency ratios typically around 2, averaging about 1.8:1, and the observed onset time of the fundamental wave often has a time delay of about 1 second relative to the harmonic wave [53, 60–61]. The same confusion exists in observations of source region positions for Type III burst fundamental and harmonic radiation as for Type II bursts, i.e., the observed source regions of fundamental and harmonic waves with the same frequency sometimes appear at the same height [61–62].

In the 1950s and 1960s, when solar radio phenomenon observations and theoretical research began to rise and flourish in Australia, limited by understanding and knowledge of solar atmospheric structure, people indeed had sufficient reasons to abandon the physically simple and effective ECM radiation mechanism and had to seek the complex and profound nonlinear wave-wave coupling processes and inefficient plasma radiation mechanisms. This was because the widely accepted solar atmospheric models at the time generally underestimated the importance of coronal magnetic fields, completely denying the possibility that Martyn [63] first proposed—that solar superthermal radio radiation originates from electron plasma electrostatic oscillations (i.e., Langmuir wave) instability. Wild et al. [64–66] introduced the term "Plasma Emission" when first classifying SRB phenomena by dynamic spectral characteristics to specifically describe these SRB radiations. The first actually possible plasma oscillation radiation mechanism was proposed by Field [67], who suggested that Langmuir waves could couple with transverse electromagnetic waves and directly convert into transverse electromagnetic wave radiation in non-uniform plasma. However, Ginzburg et al. [33] pointed out that Field's [67] mechanism was not only too inefficient but also could not produce harmonic radiation, and proposed that Langmuir waves produce transverse electromagnetic wave emission through thermal ion scattering (or ion acoustic wave coupling), which is more efficient and can produce second harmonics. Subsequent plasma radiation theories basically adhered to this basic physical picture of Ginzburg et al. [33], with details being gradually modified to become increasingly complex and profound [54–56]. For example, to resolve conflicts with observational phenomena, it became necessary to introduce a series of new complex states and processes such as "marginal instability," "clump Langmuir waves," and "stochastic growth theory" [68–70].

In fact, since the 1970s, space satellite observations of the corona, especially high-resolution observations since the 1990s, have painted a completely new physical picture of the corona as a highly non-uniform and non-equilibrium complex magnetized plasma structure, where magnetic fields play an increasingly important role [10]. In particular, the influence of magnetic fields on SRB radiation processes should not be ignored, making it necessary to re-examine the role of ECM radiation mechanisms in SRB phenomena. Wu and collaborators have reconsidered the possibility of applying ECM radiation mechanisms to explain Type III SRB phenomena in a series of works [14, 16, 71–72]. In their theoretical models, they introduced an important concept: assuming the existence of some low-density cavity ducts in the solar atmosphere that originate in the low solar atmosphere and may extend all the way to interplanetary space. This assumption is consistent with the filamentary structures ubiquitously shown in high-resolution coronal observations, and they further proposed two possible mechanisms for the formation of such low-density cavity ducts: one is thermal pressure from heating by high-energy particle beams, and the other is magnetic pressure formed by magnetic field perturbations [73]. Their basic physical idea for Type III SRB generation can be described as follows: ECM radiation produced by high-energy electron beams within low-density ducts is confined within the ducts and propagates outward along them until the radiation frequency exceeds the cutoff frequency outside the duct and escapes. An important new phenomenon in this picture is that the initial excitation source of Type III SRBs (deeper inside the duct) and the observed apparent radiation source (at the duct escape point) are obviously at different atmospheric heights [14]. Based on this picture, a series of observational phenomena such as "overlapping observed source regions of same-frequency fundamental and harmonic waves, harmonic-to-fundamental frequency ratios less than 2, and time delays of fundamental wave arrival relative to harmonic waves" can be self-consistently explained [14, 16].

Further considering the effects of self-generated Alfvén waves during the propagation of high-energy electron beams along magnetic fields, Wu et al. [8] proposed a self-consistent ECM radiation theoretical model in which self-generated Alfvén waves have three main effects on ECM radiation mechanisms: first, the wave pressure of self-generated Alfvén waves displaces background plasma and spontaneously forms a low-density cavity duct along the high-energy electron beam; second, the interaction between self-generated Alfvén waves and high-energy electron beams creates a new excitation source for ECM radiation in O-mode waves, significantly affecting the polarization state of ECM radiation; third, the pitch-angle scattering of high-energy electron beams by self-generated Alfvén waves significantly changes the velocity distribution of high-energy electron beams, providing them with higher free energy for ECM instability excitation. These three effects can all play positive and effective roles in overcoming the three major obstacles frequently encountered when applying traditional ECM radiation mechanisms to SRB phenomena: "escape difficulty, excitation difficulty, and polarization difficulty."

Recently, Chen et al. [9] further proposed a new physical model for Type III SRB phenomena based on this new self-consistent ECM mechanism. In this model, the driving free energy mainly comes from the steepened distribution in the low-energy segment of the high-energy electron beam energy spectrum and the perpendicular energy broadening caused by pitch-angle scattering from self-generated Alfvén waves. Assuming a self-generated Alfvén wave intensity reaching saturation level $\delta\mathrm{B}^2/\mathrm{B}_0{}^2 = 0.05$, an "escape parameter" $\omega\{ce\}/\omega\{\mathrm{pe}\} = 5 > 1$ inside the low-density cavity duct, and high-energy electron beam power-law index, steepening index, and characteristic velocity in the high-energy segment of $\alpha = 3$, $\delta = 6$, and $\mathrm{v}_0 = 0.4\mathrm{c}$, respectively. In addition to self-consistently and reasonably explaining the main observational characteristics of Type III SRBs, similar to the models of Wu et al. [14, 16], the calculation results of Chen et al. [9] also show that the polarization of fundamental wave radiation is significantly higher than that of harmonic wave radiation, which is consistent with observational statistical results for Type III SRBs [57, 62].

Additionally, there is a subclass of Type III SRBs that exhibits fine structures, called Type IIIb SRBs [53, 74–75]. Figure 4 [Figure 4: see original paper] presents a comparison between the dynamic spectrum of a Type IIIb SRB and the distribution of ECM radiation growth rates, where L__b is the initial length of the non-thermal electron beam. The figure shows that the spectrum of Type IIIb bursts exhibits quasi-periodic variations. Assuming that the high-energy electron beam exciting the radiation is modulated by a quasi-monochromatic Alfvén wave, Zhao et al. [18] calculated in detail the variation of ECM radiation growth rates during the propagation of high-energy electron beams. The results show that under appropriate parameters (such as quasi-monochromatic Alfvén wave relative amplitude A = 0.224, characteristic wavelength λA = *7500 km; high-energy electron beam characteristic velocity* v_0 *= 0.3c; escape parameter* ω{ce}/ω_{pe} = 1.25, etc.), the model calculations can well simulate quasi-periodic variations similar to observational results (as shown in the right panel of Figure 4).

6 ECM Radiation from Shock-Accelerated Electrons along Expanding Loops and Type IVm SRB Phenomena

In the analysis of observations from the Nancay Radio Observatory interferometer in France, Boischot [76] first discovered a class of meter-wave continuous spectrum radiation that was clearly different from Type I SRBs in that they were radiated by sources moving outward in the corona, usually appearing after flares or coronal mass ejections, with motion speeds similar to those of narrow-band line-spectrum Type II SRBs at approximately 10^3 km/s. Because their dynamic spectral characteristics were significantly different from the previously discovered Types I, II, and III SRBs, Boischot et al. [77] called them Type IV SRBs. Subsequently, observational analysis by Wild et al. [78] further confirmed that these Type IV SRBs were burst radiations with relatively broad, smooth continuous spectra following Type II SRBs, and that radiation at all frequencies seemed to come from the same location, with the radiation source position moving outward steadily throughout the entire radiation duration at speeds of the same order as Type II SRBs [79]. In fact, such Type IV SRB events had been observed by Payne-Scott et al. [80] before Boischot [76], but because their radiation sources had motion characteristics similar to Type II SRBs, they were mistakenly identified as Type II SRB events. Unfortunately, the classification name “Type IV burst” initially suggested by Boischot et al. [77] quickly became fashionable and popular, with almost all continuous spectrum burst radiations associated with flares being called Type IV bursts, even though some continuous spectrum radiation sources were statically located above flares without any motion characteristics, making them completely different from the moving characteristic Type IV bursts initially suggested by Boischot et al. [77]. Weiss [81] further introduced “moving” Type IV bursts (IVm) and “stationary” Type IV bursts (IVs) to distinguish these two different types of continuous spectrum burst phenomena. However, people are more interested in IVm bursts because they have more obvious physical connections with coronal mass ejections and even became one of the main research targets of early space observations on space stations Skylab and Solar Maximum Mission (SMM) satellite [82].

The observational characteristics of IVm bursts are relatively complex. The observed frequency distribution is similar to Type II bursts, ranging from several hundred MHz at the high-frequency end to one or two tens of MHz at the low-frequency end, with continuous radiation durations generally of several tens of minutes, sometimes lasting several hours [83–84]. The brightness temperature and polarization state of IVm bursts both show temporal variations during the radiation duration: brightness temperature first increases in the first few minutes and then gradually decreases with time, with maximum brightness temperatures around 10^{10} K, while the degree of polarization continues to increase with time, often reaching over 90% by the end of the burst [85–87]. Based on differences in radiation source structure, Smerd et al. [88] further divided IVm bursts into three subtypes: first, "isolated source," generally consisting of an unpolarized source that splits into two sub-sources with opposite polarities while moving outward, sometimes with sub-source numbers reaching three or more, all having the same polarity; second, "expanding arch," usually composed of three sub-sources distributed on a magnetic loop, with two located at the loop footpoints or legs having opposite polarities and another at the loop top generally having no polarity; third, "advancing front," where the source of this type of IVm burst is located on the outer expanding shell of the Type II burst source [89].

Research on the radiation mechanism of IVm bursts is also one of the most controversial focal points. Boischot et al. [77] initially proposed that IVm bursts were produced by synchrotron radiation from relativistic electrons trapped in high coronal magnetic fields at high harmonics, but later two-dimensional radio heliograph observations found that IVm bursts have strong circular polarization characteristics, contradicting the linear polarization features of synchrotron radiation. Therefore, some proposed that IVm bursts were produced by gyrosynchrotron radiation from lower-energy sub-relativistic electrons (energy $E < 1$ MeV) at low harmonics (harmonic number $n < 10$) [90–94], but subsequent observations found that the brightness temperature of IVm sources was several times higher than expected from gyrosynchrotron radiation [86]. To explain the higher brightness temperature, Duncan [95] proposed that coherent plasma radiation was the most likely radiation mechanism for IVm bursts. To explain polarization variations, Melrose [32] proposed a mixed radiation mechanism, i.e., initially dominated by plasma radiation at the second harmonic, later dominated by gyrosynchrotron radiation. However, many issues remain controversial, such as what causes the various different structural morphologies, why polarization shows a gradually increasing variation pattern, and what the physical mechanism of brightness evolution is.

Based on the widely recognized observational fact that IVm bursts have close connections with Type II bursts and coronal mass ejections, combined with the motion characteristics of radiation sources and evolution characteristics of radiation spectra during IVm burst radiation processes, Tang et al. [96] proposed that ECM radiation from high-energy electron beams trapped in moving coronal loops serves as the model mechanism for generating IVm burst radiation. Unlike previous studies, the authors considered the influence of propagation dynamic evolution effects of high-energy electron beams trapped in coronal loops, as well as the possible effects of coronal loop structure and its motion on the ECM radiation process. For example, high-energy electron beams gradually lose energy due to collisions, radiation, and other processes during propagation, causing their energy and velocity distributions to evolve. On the other hand, background plasma parameters in coronal loops not only change during the motion of high-energy electron beams but also change correspondingly due to structural evolution during the outward expansion and motion of the loops. These parameter changes may ultimately affect the ECM radiation process driven by high-energy electron beams.

Figure 5 [Figure 5: see original paper] shows the magnetic configuration of the Type IV burst source region proposed by Tang et al. [96], where RS refers to the radio source. The physical picture can be briefly described as follows: when a coronal mass ejection propagates outward at a speed greater than the fast magnetosonic wave speed, it will drive a shock wave at its front and cause electron acceleration to continuously produce high-energy electrons. Some of these shock-accelerated high-energy electrons move along open magnetic field lines near the shock and produce Type II SRBs, while others enter closed magnetic fields, enter outward-moving and expanding coronal loops, and become trapped and retained within the loops, moving along them. It is precisely these high-energy electrons trapped and moving within coronal loops that produce IVm burst radiation. Considering the energy loss of high-energy electron beams during propagation along coronal loops and the magnetic mirror effect of changing coronal loop magnetic fields, the distribution function at height h can be written as [96]:

F_{b1}(u_1;) = A_b [1 - e^{(1-σ_h)(1- ^{2})/ _c^2}] × [1 + ($u_1{}^2$/u_c^2)^{δ/2}]^{-α} × exp[-(- _c)^2/Δ ^{2}]

where u_1 is the specific momentum of electrons at height h, _E ΔE/E_c, Δ , and σ_h are the energy loss of high-energy electrons (normalized by cutoff energy), pitch-angle dispersion of velocity distribution, and coronal loop magnetic mirror parameter, respectively, all generally being functions of height h along the coronal loop.

The above distribution function (2) describes the evolution of the velocity distribution of high-energy electron beams during propagation along coronal loops, where the free energy driving ECM instability mainly comes from three aspects: the steepened energy distribution in the low-energy segment of the electron power-law energy spectrum, the velocity loss-cone distribution caused by the coronal loop magnetic mirror effect, and coronal loop background plasma perturbations (such as turbulent Alfvén waves). Tang et al. [96] considered the evolution processes of the first two driving factors within the coronal loop. The corresponding analysis and calculation results show that in the initial stage when high-energy electron beams enter the coronal loop, the energy spectrum steepening driving effect dominates the free energy component. As energy loss occurs during propagation within the loop, the contribution of energy spectrum steepening effects becomes smaller. At the same time, as propagation within the loop gradually deepens, the coronal loop magnetic mirror effect becomes stronger, making the loss-cone distribution free energy increasingly important and even becoming the main factor driving ECM instability. Throughout the entire expansion process of the coronal loop moving outward with the shock wave, shock-accelerated electrons continuously enter the coronal loop and propagate while being trapped within it. As a result, under certain parameter conditions, continuous radiation forms along the magnetic loop, while under other parameter conditions, several discrete radiation source regions may evolve within the coronal loop, which is likely the reason why IVm bursts have different structures.

7 ECM Radiation from Reconnection-Accelerated Electrons along Coronal Loops and Type V SRB Phenomena

Similar to Type IV continuous spectrum burst radiation that follows Type II SRB phenomena, there also exists a class of continuous spectrum burst phenomena that follow Type III SRB phenomena, called Type V SRBs. This new type of burst phenomenon was first noted by Wild et al. [78], followed by extensive observational studies of their characteristics [97–99]. Comprehensive observational analyses show that Type V SRB phenomena have the following characteristics [53]:

(1) Type V bursts often occur immediately after Type III bursts or Type III burst groups, with source region heights and frequency ranges similar to the preceding Type III bursts, but with horizontal positions of the source region clearly separated from the preceding Type III bursts by intervals of about a few tenths of a solar radius;

(2) The radiation source size of Type V bursts increases rapidly with decreasing radiation frequency and is much larger than that of the preceding Type III bursts, thus their brightness temperature is about an order of magnitude lower than that of Type III bursts. The radiation bandwidth is generally around 100 MHz, comparable to the radiation frequency, thus appearing as continuous spectrum radiation, generally ranging from one or two hundred MHz down to several MHz;

(3) Similar to how the duration of Type IV bursts is much longer than that of Type II bursts, the duration of Type V bursts is also much longer than that of Type III bursts, increasing with decreasing frequency, generally from about 40 s at 200 MHz to about 200 s at 20 MHz, but significantly shorter than the duration of Type IV bursts, just as the duration of Type III bursts is significantly shorter than that of Type II bursts;

(4) The polarization degree of Type V bursts is generally relatively low, but

usually has opposite polarization states to their preceding Type III bursts, and the larger the distance between the two radiation sources, the more likely their polarization states are to be opposite. This is also the most puzzling obvious characteristic of Type V bursts.

At the beginning of Type V burst discovery, synchrotron radiation from relativistic electrons was also proposed as their generation mechanism [97]. However, further calculations quickly showed that such a large range of relativistic high-energy electrons could not exist in the solar atmosphere even during large flares [100–103]. Therefore, most later discussions followed the plasma radiation model for high-energy electrons trapped in coronal loops initially proposed by Weiss et al. [102]. During this period, Winglee et al. [104] discussed the possibility that Type V bursts are produced by high hybrid waves excited by ECM instability and then converted into electromagnetic radiation through mode conversion, while the preceding Type III bursts are still produced by plasma radiation mechanisms. Although the structure and evolution of Type V bursts are not as complex as those of Type IV bursts, there are still many controversial issues, especially the question of how Type V bursts are related to their preceding Type III bursts, which has not been reasonably explained to date. For example, why are the radiation source regions of Type V bursts and their preceding Type III bursts so far apart, what causes the opposite radiation polarization states between Type V bursts and their preceding Type III bursts, what factors determine the radiation duration of Type V bursts, and why is it significantly longer than that of their preceding Type III bursts?

Considering the close relationship between Type V bursts and Type III bursts, similar to the associated generation model between IVm bursts and Type II bursts, Tang et al. [105] suggested that Type V bursts and Type III bursts are also jointly produced by a similar associated model, except that the high-energy electrons here originate from magnetic reconnection acceleration in flares rather than from shock acceleration that links IVm bursts with Type II bursts [96]. According to the standard flare model, magnetic flux tubes emerging from the solar photosphere into the corona become newborn coronal loops with closed magnetic field structures, connecting with original coronal magnetic field structures to form a reconnection configuration, leading to magnetic reconnection. The energy release from this magnetic reconnection process drives flare eruptions through some physical mechanism that accelerates charged particles. Although the specific physical acceleration mechanism is still unclear, the series of consequences produced by high-energy particles, especially high-energy electron beams, as direct products have been widely observed as flare radiation phenomena. The most prominent among these are hard X-ray flares and Type III SRB phenomena: the former is bremsstrahlung produced by high-energy electron beams propagating inward along coronal magnetic fields when they impact relatively dense regions, while the latter is an induced radiation phenomenon caused during outward propagation along coronal open magnetic fields. Due to the complex magnetic field configuration near the magnetic reconnection region, some high-energy electrons inevitably enter closed magnetic fields, become trapped in coronal loops, and propagate along them. The ECM radiation excited by these high-energy electron beams trapped and propagating in coronal loops through ECM instability is precisely the radiation excitation source of Type V bursts.

In the model of Tang et al. [105], the driving free energy for ECM radiation excited by high-energy electron beams trapped and propagating in coronal loops is similar to the case of IVm bursts [96], also mainly coming from three aspects: the steepened energy distribution in the low-energy segment of the power-law energy spectrum of reconnection-accelerated electrons, the velocity loss-cone distribution caused by the coronal loop magnetic mirror effect, and possible turbulent Alfvén waves within the coronal loop. Additionally, in the case of shock-accelerated Type II and IVm bursts, since shock acceleration processes can continuously accelerate and produce high-energy electrons, the corresponding Type II and IVm burst radiations can last for longer times. In contrast, in the case of reconnection-accelerated Type III and Type V bursts, since high-energy electron production by reconnection acceleration has intermittent characteristics and cannot continuously accelerate like shocks, the durations of Type III and Type V bursts are much shorter than those of Type II and IVm bursts, respectively. In fact, the radiation duration of Type V bursts can be estimated by the effective propagation lifetime of reconnection-accelerated high-energy electron beams after entering coronal loops. If energy loss of high-energy electron beams during propagation in coronal loops is mainly caused by collisions, then for a background plasma temperature of T 100 eV and densities of n 5 × 10^8 cm^{-3} and 10^8 cm^{-3}, the corresponding collisional energy loss rates for typical high-energy electrons with energy of 25 keV are $\dot{v}$ 2 × 10^{-2} s^{-1} and $\dot{v}$ 4 × 10^{-3} s^{-1}, respectively, with corresponding high-energy electron effective lifetimes of t_D = $\dot{v}^{-1}$ 50 s and 250 s. These are of the same order as the typical radiation lifetimes of Type V bursts at high and low frequencies, respectively, implying that the variation of Type V burst radiation lifetime with frequency may be caused by the variation of effective propagation lifetime of high-energy electron beams with radiation source height [105].

Figure 6 [Figure 6: see original paper] shows three possible positional relationships of Type V burst radiation sources relative to Type III burst sources. Regarding the observed large horizontal separation between radiation sources and the anti-correlation between polarization states of Type V bursts and Type III bursts, according to the model of Tang et al. [105], it can be explained as follows: high-energy electrons produced by flare magnetic reconnection acceleration propagate partly along open magnetic fields outward and partly along closed magnetic fields into coronal loops, both producing Type III and Type V bursts through ECM radiation mechanisms, respectively. The polarization state of Type V bursts is related to the radiation position of high-energy electron beams propagating in coronal loops: (1) when located near the open magnetic field side (as shown in Figure 6(a)), since the magnetic field directions of the two source regions are roughly the same, their polarization states are also almost identical; (2) if located in the coronal loop top region (as shown in Figure 6(b)), Type V bursts have almost no polarization due to left-right symmetry of the radiation source position; (3) when located on the side far from open magnetic fields (as shown in Figure 6(c)), the magnetic field direction in the Type V burst radiation source region will be opposite to that of Type III bursts, thus its polarization state will also be opposite. Active regions causing flare eruptions are usually large sunspot regions with strong magnetic fields in the solar atmosphere, where coronal loop scales are generally large, spanning a fraction of the solar surface. The model image presented in Figure 6 not only explains why Type V burst radiation sources have almost the same atmospheric height as Type III burst radiation sources but with far different horizontal distances, but also clearly explains why they show opposite radiation polarization states and why larger horizontal separation makes opposite polarization states more likely.

8 ECM Radiation from Magnetically Confined Energetic Electrons in the Low Corona and Microwave SRB Phenomena

In the solar radio radiation spectrum, microwave bursts typically refer to radio burst radiation with frequencies f $>$ 1 GHz (or wavelengths $\lambda < 30$ cm). In Sections 3–7 above, we mainly re-examined the applicability of ECM radiation mechanisms for traditional Type I to V meter-wave SRBs, whose radiation source regions are mainly located in the high corona above 100,000 km from the solar surface. When we turn our attention to the low corona below 100,000 km, especially active regions in the low corona, we find that the solar plasma atmosphere there has more complex magnetic field structures, and high-energy electron beams constrained within them are in more complex motion states, causing the microwave SRBs they excite to also exhibit more complex spectral fine structure phenomena, such as: bidirectional microwave Type III burst pairs, microwave spike bursts, microwave fiber bursts, microwave drifting pulses, microwave zebra patterns and zebra-like structures, V-type, N-type, and M-type bursts, and microwave pulsation structures [1, 106–108]. These fine structures are directly related to the structural evolution of magnetic fields in low coronal active regions, especially interactions between complex magnetic structures including magnetic reconnection, which are the direct causes of magnetic energy release and flare eruption activities in the solar atmosphere. Therefore, observational studies of microwave SRBs, especially their fine structures, can provide us with important information about solar magnetic field structure and evolution, particularly the physical processes of solar eruption activities, and have always been a hot research field in solar physics. For example, so-called “bidirectional microwave Type III burst pairs” composed of simultaneously appearing forward (from high to low frequency) drifting and reverse (from low to high frequency) drifting microwave Type III bursts are believed to be directly produced by bidirectional high-energy electron beams accelerated by magnetic reconnection regions and propagating outward and inward from the reconnection point

[109–111]. So-called “spike bursts” with rapid fine structures are believed to be possibly directly related to the “elementary process” of high-energy electron acceleration in solar eruption activities, because they have prominent coherent characteristics such as short duration (only milliseconds), narrow relative bandwidth ($< 1\%$), high radiation polarization degree (nearly 100%), and high radiation brightness temperature (reaching 10^{13}–10^{15} K) [27, 112–114].

Due to the complex and diverse fine structures of microwave SRBs, research on microwave burst radiation mechanisms is also very complex, with various models for specific fine structures emerging continuously [108, 111, 115–118]. In fact, these fine structures generally originate from magnetic active regions with strong and complex magnetic fields, so magnetic fields should also play an important role in their radiation mechanisms. Therefore, we believe that the radiation mechanisms producing these fine structures essentially belong to ECM radiation mechanisms where magnetic fields play a major role, and the complex and diverse observational characteristics of dynamic spectral fine structures precisely reflect the physical essence of diverse magnetic field structures in the radiation source region. Here, we attempt to illustrate the possibility of using ECM radiation mechanisms to explain fine structure phenomena in SRBs by referring to a typical observational example discovered by the solar broadband radio spectrometer of the National Astronomical Observatories, Chinese Academy of Sciences (NAOC).

The solar broadband radio spectrometer of NAOC has an observation frequency range in the microwave band of 0.7–7.6 GHz and is designed with a high-resolution observation mode with corresponding time resolution of 1.25 ms and frequency resolution of 4 MHz, having discovered many interesting fine structure phenomena [1]. Wu et al. [119] discovered a new class of short-timescale, narrow-bandwidth, slowly-drifting pulse bursts in the analysis of its high-resolution observational data, called “solar microwave drifting spikes.” Figure 7 shows a typical event observed on November 3, 2004 [119], where 65 drifting spikes form a drifting spike group, with individual spike durations all less than 100 ms (average 42.3 ms), relative bandwidths $\Delta f/f < 1\%$ (average 0.44%), and frequency drift rates of several hundred MHz/s (average 247 MHz/s). Additionally, the upper and lower panels in the figure show the left- and right-handed circular polarization components of spike radiation, respectively, with almost identical intensities meaning these spike radiations are unpolarized. These characteristics are clearly different from previous similar events. For example, their short timescale and narrow bandwidth features are similar to known spike bursts, but their frequency drift rates are an order of magnitude slower than spike bursts; their frequency drift rates are similar to known fiber bursts, but their durations and relative bandwidths are much smaller than fiber bursts.

Wu et al. [119] pointed out that: (1) the slow frequency drift implies that the motion speed of radiation sources cannot be the propagation speed of high-energy electron beams themselves but is more likely the propagation speed of some wave structure in the solar atmosphere; (2) the narrow bandwidth characteristic close to the natural bandwidth of ECM radiation [120] indicates that high-energy electrons in the radiation source have very high coherence, meaning they are constrained within the same isolated structure, with the structure scale being about a few thousandths of the local magnetic field non-uniformity scale [114]. Combined with plasma parameters of the low coronal environment of the solar atmosphere, we suggest that such drifting spike events may be ECM radiation excited by electrons constrained in kinetic Alfvén solitary waves. Alfvén waves are low-frequency electromagnetic fluctuations ubiquitous in the solar atmosphere, which can transform and develop into kinetic Alfvén solitary waves when propagating outward [121]. Figure 8 [Figure 8: see original paper] below depicts the typical physical structure of such kinetic Alfvén solitary waves [119], where panels (a), (b), (c), and (d) show the distributions of electron density (n), parallel electric field (E_z), field-aligned potential (Φ_z), and electron velocity (v_{ez}) within the solitary wave, respectively.

As can be seen from Figure 8, the transverse scale of kinetic Alfvén solitary waves is about 50λe *(where* λe is the local electron inertial length), while electrons within the solitary wave can be accelerated by the solitary wave electric field along the field direction to about 20v_A and be constrained to oscillate rapidly along the magnetic field within the solitary wave potential well. Simultaneously, due to the pitch-angle effect of kinetic Alfvén solitary waves and background Alfvén wave turbulence, the velocity distribution of these field-aligned fast electrons rapidly broadens in the direction perpendicular to the magnetic field, forming a shell-like distribution, thus providing effective driving free energy for exciting ECM instability. In this way, each kinetic Alfvén solitary wave is an effective exciter of ECM radiation and thus a producer of drifting spikes. The drift speed of spikes is determined by the propagation speed of kinetic Alfvén solitary waves, i.e., the local Alfvén velocity, while the lifetime of drifting spikes will be determined by the lifetime of solitary waves. Based on appropriate models of sunspot magnetic fields and relevant observational parameters, the local Alfvén velocity in the radiation source region can be estimated to be about 6×10^3 km/s, so the average energy of electrons constrained in solitary waves is about 20v_A   0.4c   50 keV, corresponding to typical energies of high-energy electrons in solar microwave bursts. According to Voitenko et al. [122], the propagation damping rate of kinetic Alfvén waves in the solar atmosphere is γ 0.5v_e k ^{2} *20 Hz, where k* is the component of the wave vector perpendicular to the magnetic field direction, and the propagation lifetime of kinetic Alfvén solitary waves can be roughly estimated as τ γ^{-1} 50 ms, which basically matches the average lifetime of observed drifting spikes. Additionally, based on the observed average relative bandwidth Δf/f   0.44%, the scale of individual drifting spike radiation sources can be estimated as: l   (Δf/f)L   4 km [114], where L   1000 km is the characteristic scale of magnetic field non-uniformity in the source region. At the same time, we note that this scale is much larger than the transverse scale of kinetic Alfvén solitary waves 50λ_e   10 m, meaning that the geometric structure of kinetic Alfvén solitary waves inferred from observations indeed conforms to the quasi-perpendicular propagation characteristics of kinetic Alfvén waves under low-β parameter conditions [123].

9 Summary and Outlook

Radio waveband observational phenomena in celestial bodies are extremely rich, with very active radio radiation sources in various celestial bodies from planets, the Sun, to galaxies and quasars. Many problems remain to be explained in radio radiation mechanism theory, making it the most complex electromagnetic radiation mechanism in astrophysics [124]. Particularly, those small-scale, short-timescale, high-brightness radio burst radiations closely associated with cosmic celestial body eruption activities are widely believed to be induced radiation processes driven by plasma instability and carry rich physical information about the structural state and activity processes of the plasma in the radiation source region. Within the solar system, a large variety of radio burst radiation phenomena from solar radio bursts and planetary magnetosphere radio radiation to interplanetary radio bursts provide rich experimental samples for studying the physical theories of celestial radio burst phenomena. Based on existing plasma theory, there are mainly two types of induced radiation mechanisms: one is the plasma radiation mechanism, where high-energy electron beams excite Langmuir waves, which then drive nonlinear wave mode conversion processes to produce radio radiation; the other is the ECM radiation mechanism, where high-energy electron beams directly excite radio radiation. Since these two induced radiation mechanisms were proposed in the late 1950s, extensive theoretical research has been conducted on them in combination with observations of various radio burst radiation phenomena within the solar system, and they still each have their own merits and remain controversial to this day.

In Earth's AKR phenomena, since the proposal of the Wu-Lee model [2] in 1979, the ECM radiation mechanism has been widely accepted as the basic radiation mechanism for general planetary magnetosphere radio radiation phenomena due to extensive verification by space satellite in-situ detection results of its radiation source region. However, in solar radio burst phenomena, due to some difficulties of traditional ECM radiation mechanisms, plasma radiation mechanisms remain the widely discussed basic radiation mechanism. Nevertheless, Wu [123] first discovered that turbulent Alfvén wave perturbations ubiquitous in space and astrophysical plasma environments could have important effects on traditional ECM radiation mechanisms and cause qualitative changes in basic physical images such as driving free energy and radiation polarization state of ECM radiation excitation. In particular, subsequent series of studies further found that the new self-consistent ECM radiation mechanism considering Alfvén wave effects can effectively overcome the main difficulties frequently encountered when applying traditional ECM radiation theory to solar radio burst phenomena [8–9, 12, 18, 34, 50, 125–127].

Wu et al. [8] considered the influence of Alfvén waves excited by beam current instability on cyclotron maser radiation, well solving two basic difficulties in maser radiation application to solar radio bursts, and proposed a self-consistent ECM radiation model: when high-energy electrons propagate along magnetic fields in the solar atmosphere, they can produce beam current instability and excite Alfvén waves. Therefore, background plasma is displaced along the electron beam propagation direction under Alfvén wave pressure, forming a low-density duct. Within the duct, due to low density and strong magnetic field, the excitation condition for ECM radiation is easily satisfied, i.e., plasma frequency is less than electron cyclotron frequency. On the other hand, under the pitch-angle scattering effect of self-generated Alfvén waves, the velocity space distribution of high-energy electron beams changes, such as forming crescent distributions, providing free energy for ECM radiation.

After proposing the new free energy and self-consistent model for ECM radiation, we re-examined the physical processes of some solar radio burst phenomena: solar radio Type I bursts are generally believed to be produced by high-energy electrons trapped in coronal loops. Zhao et al. [34] considered the influence of Alfvén waves on ECM radiation and found that the dominant radiation mode changed from X-mode to O-mode, well explaining the observed O-mode circular polarization characteristics of Type I bursts. Considering the influence of Alfvén waves generated by ion beams accelerated by shocks, Zhao et al. [50] established a physical model for solar radio Type II bursts excited by shock-accelerated high-energy electrons, well explaining solar radio Type II bursts. Chen et al. [9] considered the effect of Alfvén waves self-generated by beam electrons and could self-consistently explain the radiation process of Type III radio bursts. Considering the evolution of electron beams moving in flare loops, Tang et al. [96] established a possible radiation model for moving Type IV bursts. Combining the relationship between Type V bursts and Type III bursts, Tang et al. [105] established a magnetic configuration model for Type V burst source regions where open magnetic field lines and closed coronal loops are connected. High-energy electrons are produced at the connection position between open fields and loops, and based on ECM radiation, the model can well explain some observational characteristics of Type V bursts.

Electron cyclotron maser radiation can explain solar Type I–V radio bursts and some radio fine structure phenomena, showing good application prospects. Especially after considering the influence of Alfvén waves on ECM radiation, the excitation difficulties of radiation in solar atmospheric plasma have been reasonably solved, and the physical model has become more self-consistent. Of course, ECM radiation theory still has many unresolved difficulties. For example, the true level of Alfvén waves in radiation source regions is still difficult to determine, which awaits further development of Alfvén wave theoretical research and observational equipment. With the continuous improvement of telescope resolution, radio burst phenomena are becoming increasingly complex, accompanied by more and more fine structure phenomena. The radiation mechanisms of these radio fine structures need further exploration. Moreover, celestial radiation processes are not isolated events but just one link in a series of celestial activity processes. Therefore, as the radiation source of radio burst phenomena, high-energy electrons' acceleration process, transport and evolution process in plasma, and scattering and absorption during radiation propagation, including the dynamic evolution of radiation spectra, all require further in-depth research.

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