Advances in Kinetic Alfvén Wave Generation and Heating in the Solar Atmosphere: Postprint

Authors: Xiang Liang, Wu Dejin, Chen Ling

Date: 2023-07-14T00:00:00+00:00

Abstract

Kinetic Alfvén waves are dispersive Alfvén waves whose perpendicular wavelength approaches the ion gyroradius or electron inertial length. Due to their spatial scale being comparable to particle kinetic scales, kinetic Alfvén waves play a significant role in energization phenomena such as heating and acceleration in solar and space plasmas. Consequently, they are widely regarded as candidates for coronal heating. This study conducts an in-depth and systematic investigation into the excitation and dissipation mechanisms of kinetic Alfvén waves in the solar atmosphere. Based on the coronal plasma environment, several common excitation mechanisms are presented: temperature anisotropy instability, field-aligned current instability, electron beam instability, density inhomogeneity instability, and resonant mode conversion. Additionally, the dissipation mechanisms of kinetic Alfvén waves in the solar atmosphere are discussed, along with their implications for sunspot heating, coronal loop heating, and coronal plume heating. This work not only provides a sound theoretical foundation for understanding the driving mechanisms, kinetic evolution characteristics, and wave-particle interactions of kinetic Alfvén waves in the solar atmosphere, but also contributes to elucidating the microscopic physical mechanisms underlying energization phenomena such as energy storage and release and particle heating in coronal plasmas.

Full Text

Preamble

Vol. 64 No. 3
May, 2023

Acta Astronomica Sinica

Research Progress on the Generation and Heating of Kinetic Alfvén Waves in the Solar Atmosphere

XIANG Liang[1], WU De-jin[2], CHEN Ling[2]
(1 Institute of Space Physics, Luoyang Normal University, Luoyang 471934)
(2 Key Laboratory of Planetary Sciences, Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210023)

Abstract

Kinetic Alfvén waves (KAWs) are dispersive Alfvén waves whose perpendicular wavelength approaches the ion gyroradius or electron inertial length. Because the wave scale matches the kinetic scale of particles, KAWs play an important role in energization phenomena such as plasma heating and particle acceleration in solar and space plasmas. Consequently, KAWs are frequently considered as candidates for coronal heating. This study investigates the excitation and dissipation mechanisms of KAWs in the solar atmosphere in depth and systematically. Based on the coronal plasma environment, we introduce several common KAW excitation mechanisms: temperature anisotropy instability, field-aligned current instability, electron beam instability, density inhomogeneity instability, and resonant mode conversion. We also describe the dissipation mechanisms of KAWs in the solar atmosphere and discuss their effects on heating in sunspots, coronal loops, and coronal plumes. This work not only provides a reasonable theoretical basis for understanding the driving mechanisms, dynamic evolution characteristics, and wave-particle interactions of KAWs in the solar atmosphere, but also helps reveal the microscopic physical mechanisms of energy storage and release, as well as particle heating in coronal plasmas.

Keywords: Sun: corona, Sun: atmosphere, magnetohydrodynamics, waves

1. Introduction

The corona is the outermost layer of the solar atmosphere, extending outward from the top of the transition region to several solar radii. The corona consists of tenuous, fully ionized plasma composed primarily of electrons, protons, and highly ionized ions. The temperature of the solar atmosphere is approximately ten thousand degrees in the chromosphere, but increases dramatically to millions of degrees in the corona after passing through a transition region only a few hundred kilometers thick. At coronal temperatures of millions of degrees, the plasma loses energy through various processes such as thermal conduction, radiation, and solar wind. Therefore, energy comparable to these losses must be continuously supplied to maintain equilibrium and sustain such high temperatures. While the energy for coronal heating originates from turbulent kinetic energy in the solar interior convection zone, how this energy is transported upward and dissipated as thermal energy in coronal plasma has remained a frontier and hot topic in solar physics.

Numerous physical mechanisms have been proposed to explain coronal heating, including acoustic wave heating, magnetohydrodynamic wave heating, magnetic reconnection, fast shock dissipation, turbulent heating, and Fermi heating. Biermann and Schwarzschild suggested that turbulent motions in the solar convection zone could effectively generate acoustic waves that dissipate energy and heat the corona. Due to strong magnetic fields in the solar atmosphere, acoustic wave heating was superseded by magnetoacoustic wave mechanisms. Boynton et al. proposed shock dissipation heating by magnetoacoustic waves, where footpoint motions at the photosphere base excite magnetoacoustic waves that become shocks when propagating to the top of the chromosphere, dissipating energy through classical collisions at shock fronts. However, magnetoacoustic waves become shocks before reaching the corona, making them ineffective for coronal heating. Alfvén first proposed that the high-temperature corona might result from Alfvén wave dissipation, suggesting that turbulent motions in the photosphere generate Alfvén waves whose associated currents heat the corona through Joule dissipation. However, Cowling and Piddington demonstrated that Joule and viscous damping are insufficient to dissipate Alfvén waves. The energy dissipation rate of plasma waves can only compensate for coronal energy losses when wavelengths approach meter scales, necessitating consideration of kinetic effects—hence kinetic Alfvén waves.

Kinetic Alfvén waves are dispersive Alfvén waves with perpendicular wavelengths comparable to the ion gyroradius (i) or electron inertial length (λe). Since wave frequencies are much lower than the ion cyclotron frequency, their parallel wavelengths are typically much larger than the ion inertial length, leading to pronounced anisotropy in electromagnetic polarization and propagation direction. KAWs play important roles in particle energization and filamentation phenomena in magnetized plasmas. Because their perpendicular wavelengths approach ion kinetic scales, KAWs can interact directly with ions, enabling energy exchange. Table 1 compares the properties of Alfvén waves and KAWs. For parallel-propagating Alfvén waves, both parallel and perpendicular wavelengths greatly exceed i and λe; for obliquely propagating Alfvén waves, both wavelengths also greatly exceed i and λe; for KAWs, the parallel wavelength remains much larger than i and λe, but the perpendicular wavelength approaches i or λe. A distinguishing feature of KAWs is their electric field perturbation parallel to the background magnetic field, making them crucial for acceleration and heating processes in solar and space plasmas.

In the 1970s, based on plasma kinetic theory, Chen et al. and Hasegawa et al. first studied the kinetic limit of KAWs in the plasma parameter range me/mp $< \beta < 1$, where me, mp, and β represent electron mass, proton mass, and the ratio of plasma thermal pressure to magnetic pressure, respectively. In the kinetic limit, dispersion relation corrections arise primarily from finite ion (ion-acoustic) gyroradius effects. Goertz et al. subsequently investigated the inertial limit of KAWs ($\beta <$ me/mp), where dispersion relation corrections are dominated by finite electron inertia effects. Based on two-fluid theory, Wu derived the complete dispersion relation for KAWs incorporating both ion gyroradius and electron inertia effects. In this expression, terms represent corrections from ion temperature and inertia effects, while other terms represent corrections from electron temperature and inertia effects. KAW properties differ significantly between different plasma β regimes: the kinetic regime (me/mp $< \beta < 1$) and the inertial regime ($\beta <$ me/mp).

Observational studies indicate that large-scale Alfvén waves are ubiquitous in the solar atmosphere. However, due to instrumental spatial resolution limitations, no direct observational evidence for small-scale KAWs has been obtained to date. Woo and Woo et al. studied fine structures at kilometer scales in the corona, suggesting these might be produced by KAWs. Based on data from the National Astronomical Observatories' solar broadband radio spectrometer, Wu et al. indirectly inferred characteristics of KAWs in the solar atmosphere by analyzing microwave drifting pulse events in solar radio bursts, attributing such events to KAWs and estimating wave properties: ω 1.5×10^5 Hz, λ 4 km, λ 10 m, with durations of about 50 ms.

The solar atmosphere contains complex, variable magnetic field structures, with plasma exhibiting high temperatures, non-uniformity, and states far from kinetic and thermodynamic equilibrium. These non-uniform structures and strong dynamic phenomena are generally considered energy sources that drive various plasma instabilities. Given the importance of KAWs in energy transport, their generation and excitation mechanisms have received widespread attention. Many plasma instabilities can provide free energy for KAW excitation, including proton and electron temperature anisotropy instabilities, velocity gradient and shear flow instabilities, current instabilities, proton and electron beam instabilities, magnetic field non-uniformity instabilities, and density non-uniformity instabilities. In density-non-uniform plasmas, large-scale Alfvén waves can convert to small-scale KAWs through resonant mode conversion. Additionally, nonlinear mechanisms such as turbulent cascade, parametric decay instability, and modulation instability may also excite KAWs. As understanding of KAW characteristics deepens, research on their generation mechanisms and formation processes continues to expand.

From the photosphere to the corona and solar wind, background plasma environments and parameters change significantly. Table 2 provides plasma parameters for different regions of the solar atmosphere. The plasma β value decreases from >1 in the photosphere to 1 in the corona, then increases to >1 in the solar wind. KAW excitation and dissipation mechanisms differ markedly across these β regimes. Chen et al. studied field-aligned current instabilities of KAWs across different β ranges, finding that high-β environments are more favorable for KAW growth. Hasegawa et al. noted that for $\beta < 1$, KAWs strongly heat electrons, while for $\beta > 1$, they more effectively heat ions.

Previous research has achieved important results regarding KAW excitation mechanisms and observational identification. However, the specific excitation mechanisms and wave-particle interaction processes of KAWs in the solar atmosphere remain unclear, particularly: (1) What are the drivers of KAWs in the solar atmosphere and where are they located? (2) Are KAWs in the solar atmosphere related to background particle energization? (3) How do KAWs dissipate energy, and is the carried energy sufficient to heat the corona? This review summarizes recent progress on KAW wave modes, energy sources, and dissipation mechanisms in the solar atmosphere.

2. Excitation of Kinetic Alfvén Waves in the Solar Atmosphere

KAWs serve as important energy carriers, making their excitation mechanisms particularly significant. This section focuses on several important KAW excitation mechanisms in the solar atmosphere: temperature anisotropy instability, electron beam instability, field-aligned current instability, density nonuniformity instability, and resonant mode conversion.

2.1 Temperature Anisotropy Instability

Numerous studies have shown that the firehose instability driven by temperature anisotropy is one of the most important mechanisms for exciting Alfvén waves. When finite ion gyroradius effects are considered, short-wavelength modifications of the firehose instability can efficiently generate KAWs. Based on plasma kinetic theory, Wu et al. and Chen et al. investigated the firehose instability of KAWs in detail, obtaining the dispersion equation where coefficients a, b, and d are expressed as functions of various plasma parameters including electron and ion temperature anisotropies, plasma β values, and Bessel functions. When δTe = 0, the equation represents proton temperature anisotropy instability exciting KAWs; when δTi = 0, it represents electron temperature anisotropy instability exciting KAWs.

Figure 1 [Figure 1: see original paper] shows the dependence of the growth rate ωi/ωci on the square of the perpendicular wavenumber i, with solid and dashed lines corresponding to electron and proton temperature anisotropy instabilities, respectively. The growth rate of proton temperature anisotropy instability decreases rapidly with increasing i, while the electron temperature anisotropy instability growth rate remains nearly constant. This indicates that short-wavelength corrections significantly suppress proton temperature anisotropy instability while having little effect on electron temperature anisotropy instability. Therefore, electron temperature anisotropy is more favorable for KAW growth than proton temperature anisotropy.

To investigate short-wavelength effects on KAW excitation, Wu et al. and Chen et al. studied the threshold conditions for temperature anisotropy instabilities. Figure 2 [Figure 2: see original paper] displays the growth rate ωi/ωci versus proton temperature anisotropy parameter δTi (left panel) and electron temperature anisotropy parameter δTe (right panel). Both instabilities exhibit threshold values δcTi and δcTe. When the anisotropy parameters exceed these thresholds, KAW growth rates increase with the anisotropy parameters. Additionally, as i increases, the proton temperature anisotropy instability threshold δcTi increases, while the electron temperature anisotropy instability threshold δcTe remains essentially unchanged. Thus, electron temperature anisotropy instability can more effectively excite KAWs compared to proton temperature anisotropy instability.

2.2 Field-Aligned Current Instability

Field-aligned currents are important phenomena in magnetized plasmas. Based on plasma kinetic theory, Wu et al. and Chen et al. studied KAW field-aligned current instabilities for different plasma β regimes ($\beta <$ me/mi, me/mi $< \beta <$ 1, and $\beta > 1$). The results show that field-aligned current instability depends significantly on plasma β, with KAW growth rates and excitation conditions differing markedly across β ranges. In the low-β regime ($\beta <$ me/mi), KAW field-aligned current instability has a threshold condition requiring electron drift velocity vD to exceed a critical velocity vc. In this regime, vA $>$ vTe (where vTe is electron thermal velocity), so the excitation condition requires vD $>$ vTe, making KAW excitation difficult. In the intermediate regime (me/mi $< \beta < 1$), the threshold condition is relatively low (vc $<$ vA). In the high-β regime ($\beta >$ 1), field-aligned current instability easily excites KAWs.

Figure 3 [Figure 3: see original paper] shows the growth rate ωi/ωci versus perpendicular wavenumber i for various drift velocities vD/vA = 0.05, 0.1, 0.2, 0.3, 0.4, and 0.5. The KAW growth rate increases with electron drift velocity but decreases with perpendicular wavenumber. A critical perpendicular wavenumber ci exists: when i $>$ ci, the growth rate approaches zero. As vD/vA increases, ci also increases, indicating that larger field-aligned currents are more effective for KAW excitation.

To further illustrate temperature anisotropy effects on field-aligned current instability, Figure 4 [Figure 4: see original paper] presents the growth rate ωi/ωci versus electron temperature anisotropy parameter δTe (left panel) and proton temperature anisotropy parameter δTi (right panel) for drift velocities vD/vA = 0, 0.1, 0.2, and 0.3. When vD/vA = 0 and 0.1, the electron drift velocity is below the field-aligned current instability threshold, and free energy for KAW excitation comes primarily from electron or proton temperature anisotropy. When vD/vA $>$ 0.2, wave growth rates increase with temperature anisotropy parameters, demonstrating that field-aligned current instability can effectively excite KAWs, with proton or electron temperature anisotropy providing additional free energy to enhance KAW growth rates.

For typical coronal loop plasma conditions with electron density ne 10^{15} m^{-3}, background magnetic field strength B$_0$ 10-100 Gs, and electron drift velocity vD/vA   0.1-10, the KAW growth rate is γ (0.01-0.1)ωci 10^{3}-10^{4} s^{-1}. These results indicate that field-aligned currents in coronal loops can effectively excite KAWs.

2.3 Electron Beam Instability

Beams are common plasma phenomena in space and astrophysical plasmas. Voitenko studied proton beam instability for KAW excitation, while Chen et al. investigated electron beam instability effects on KAW excitation using plasma kinetic theory. The dispersion relation and growth rate are given by complex expressions involving beam density nb, background ion density n_0, beam temperature Tb, beam drift velocity vb, background electron return flow velocity vd, and various thermal velocities. In the growth rate expression, the first bracketed term arises from resonant interaction with electron beams, the second from Landau damping by background protons, and the third from Landau damping by background electrons.

Figure 5 [Figure 5: see original paper] shows the growth rate γ/ω versus perpendicular wavenumber k i for electron beam drift velocities vb/vA = 6, 8, and 12. Electron beam instability can effectively excite KAWs, with growth rates increasing with vb/vA. Figure 6 [Figure 6: see original paper] displays γ/ωci versus vb/vA for beam densities nb/n_0 = 0.28, 0.3, and 0.32, with Landau damping neglected (left panel) and included (right panel). Growth rates increase with beam density, and Landau damping significantly reduces KAW excitation.

2.4 Density Non-Uniformity Instability

Density non-uniformity is an inherent property of solar and space magnetized plasmas. Based on two-fluid theory, Wu et al. and Chen et al. studied KAW excitation by density non-uniformity instability. The actual form of density non-uniformity in the solar atmosphere is extremely complex, and without in-situ measurements, the exact expression is difficult to determine. Considering a density profile of the form $n_0(x) = 1 + \sin(_0 x)$, where n* and $_0$ represent normalized density amplitude and characteristic scale, the normalized real frequency and growth rate can be derived.

Figure 7 [Figure 7: see original paper] shows plasma density $n_0(x)/n_0$, normalized wave real frequency ωR, and normalized growth rate ωI versus normalized spatial position $_0$ for density amplitudes n$/n_0 =$ *0.01, 0.05, 0.1, and 0.3. Wave growth rates increase with plasma density gradient and amplitude, demonstrating that density non-uniformity instability can effectively excite KAWs. Figure 8 [Figure 8: see original paper] displays* ωR *and* ωI *versus normalized density inhomogeneity spatial scale* $kx/_0$*. The real frequency and growth rate depend sensitively on both the spatial scale and amplitude of density non-uniformity. As* $kx/_0$ *increases, the growth rate first increases then decreases, reaching a maximum. The maximum growth rate remains nearly constant as density amplitude* n/n_0 increases.

2.5 Resonant Mode Conversion in Density-Non-Uniform Plasmas

In weakly density-non-uniform plasmas, direct excitation of KAWs through density non-uniformity instability becomes difficult, and resonant mode conversion of Alfvén waves becomes more effective. When waves propagate in density-non-uniform plasma, the local Alfvén velocity vA varies. As wave frequency approaches the local Alfvén frequency (ω kzvA), Alfvén resonance occurs, converting Alfvén waves to KAWs at kinetic scales.

In magnetized plasmas, Lorentz forces effectively prevent cross-field particle motion, creating density gradients perpendicular to the background magnetic field. Meanwhile, gravitational stratification produces density gradients parallel to the field. Consequently, the angle between density gradients and background magnetic fields spans a complex range in the real solar atmosphere. Using plasma kinetic theory, Xiang et al. studied resonant mode conversion for arbitrary angles between density gradients and magnetic fields, deriving a wave equation for the electric field.

Solving this equation yields an expression for the KAW electric field involving Airy functions. Figure 9 [Figure 9: see original paper] shows the wave electric field Ex/E_0 versus distance x/ i for various angles $\alpha = 20°$, 50°, 80°, 85°, and 90°. When α approaches 90°, the electric field amplitude is large; as α deviates from 90°, the amplitude decreases; for $\alpha < 20°$, the amplitude approaches zero, indicating that KAWs become difficult to excite.

Figure 10 [Figure 10: see original paper] presents the maximum electric field strength Exmax/E_0 versus angle α for different wavenumber ratios ky/kz = 0.1, 0.33, 1, 3, and 10. As α decreases from 90° to 0°, the maximum electric field decreases. For $\alpha \leq 40°$, KAW excitation becomes difficult. Figure 11 [Figure 11: see original paper] shows Exmax/E_0 versus density gradient i for various angles α. As i increases, the maximum electric field decreases, indicating that weak density gradients are more favorable for KAW generation—contrary to direct excitation by density non-uniformity instability. In resonant mode conversion, the driver is the Alfvén wave itself, with density non-uniformity providing only the resonance condition, not free energy. Larger density gradients make it difficult for Alfvén waves to cross the resonance surface, hindering effective conversion to KAWs.

Given the importance of beams in the solar atmosphere, Xiang et al. further studied Alfvén wave resonant mode conversion to KAWs in the presence of proton beams. The corresponding wave equation includes terms for proton beam density nbi, drift velocity vbi, and temperature Tbi. Solving this equation yields a KAW electric field expression. Figure 12 [Figure 12: see original paper] shows Ex/E_0 versus x/ i for various proton beam densities and drift velocities. Figure 13 [Figure 13: see original paper] displays Exmax/E_0 versus proton beam drift velocity (left panel) and density (right panel). As proton beam density or drift velocity increases, the electric field amplitude grows, indicating that proton beams can significantly affect the resonant mode conversion process and promote KAW excitation.

3. Plasma Heating Mechanisms in the Solar Atmosphere

Solar magnetic fields dominate coronal heating, but the specific mechanisms converting magnetic energy to plasma thermal energy remain unclear. Because

KAW scales are comparable to particle kinetic scales, they may play important roles in coronal plasma heating. This section details KAW heating mechanisms for sunspots, coronal loops, and coronal plumes.

3.1 KAW Heating Mechanism in Sunspot Chromospheres

Sunspots are magnetic structures on the solar surface. Strong magnetic fields suppress normal convective energy transport from beneath the photosphere, making sunspots 1000–2000 K cooler than the surrounding quiet photosphere. However, sunspot temperature increases more rapidly with height, becoming hotter than the surroundings in the chromosphere and corona. The heating mechanism of sunspots has long been a major question in solar physics. Figure 14 [Figure 14: see original paper] shows a semi-empirical atmospheric model of a sunspot (solid lines), with panels displaying temperature, electron and atom density, and ionization degree from top to bottom; dashed lines represent quiet Sun values. In the photosphere and lower chromosphere, sunspot temperatures are lower than background plasma, while in the upper chromosphere and corona they are higher. Analysis of density and ionization variations with height reveals that sunspot heating is related to charged particle density and background magnetic field strength.

Based on drift kinetic theory, Wu et al. studied the effects of acoustic and kinetic Alfvén waves on sunspot heating. Considering collisions between neutral atoms, the acoustic wave heating rate is given by QHS = mHnHcs^{2} cδn^{2}, where mH is hydrogen atom mass, nH is hydrogen atom density, cs is sound speed, c is collision frequency, and δn is acoustic wave density perturbation. Considering Joule dissipation, the KAW heating rate is QHK = menevA^{2} eiδnK^{2}, where me is electron mass, ne is electron density, ei is electron-proton collision frequency, and δnK is KAW density perturbation.

Balancing wave heating rates against radiative cooling yields the required perturbation density amplitudes for acoustic and KAW heating. Figure 15 [Figure 15: see original paper] shows the required relative density amplitude versus height, with dashed, dotted, and solid lines corresponding to KAW heating, acoustic wave heating, and combined heating, respectively. As height H increases, the required perturbation density amplitude for KAW heating decreases, while that for acoustic wave heating increases. For $H < 800$ km (photosphere and lower chromosphere), acoustic waves effectively heat sunspots; for $H > 800$ km (upper chromosphere and corona), KAWs heat sunspots more efficiently.

3.2 KAW Heating Mechanism in Coronal Loops

Coronal loops are plasma structures in closed magnetic field regions of the corona. Their magnetic structure often correlates spatially with sunspot fields, but brighter loop regions do not necessarily coincide with stronger fields. Coronal loop heating is typically non-uniform, with some loops appearing brighter near weak-field regions than near strong-field regions. The physical mechanism of coronal loop heating remains an unresolved problem in solar physics. Based on drift kinetic theory, Wu et al. studied KAW Landau damping effects on coronal loop heating. According to Hasegawa et al., the KAW Landau damping rate is given by an expression involving the ratio of Alfvén velocity to electron thermal velocity vA/vTe.

Figure 16 [Figure 16: see original paper] shows the KAW Landau damping rate γ/ω versus vA/vTe. For $0.1 <$ vA/vTe < 2.5, Landau damping occurs effectively, with maximum damping when vA/vTe 1, indicating strongest Landau resonant interaction. KAW dissipation mechanisms also depend sensitively on background plasma parameters. Considering the relationship between perturbed magnetic field in the y-direction and background field, Wu et al. derived the KAW heating rate expression Q = Qm[ω /(kz^{2}vA^2)], where = kx^2 when vA $>$ vTe and = kx^2 when vA $<$ vTe, with kx and λe representing the x-direction wavenumber and electron inertial length.

Figure 17 [Figure 17: see original paper] shows the KAW heating rate Q/Qm versus background magnetic field strength B_0 for different plasma parameters $\alpha = 0$, 0.5, and 1. The left panel represents loop top conditions, the right panel loop footpoint conditions. KAW heating rates correlate strongly with background magnetic field strength. The effective heating range at loop tops is larger than at footpoints, explaining why some loops appear brighter at their tops and in weak-field regions than in strong-field regions.

Based on plasma kinetic theory, Xiang et al. further studied KAW effects on coronal loop heating in the presence of proton beams. Figure 18 [Figure 18: see original paper] shows the heating rate Qm/Q_0 versus proton beam drift velocity vbi/vA (left panel) and density nbi/n_0 (right panel). As proton beam density or drift velocity increases, the KAW heating rate increases, indicating that proton beams enhance KAW heating rates. For realistic coronal conditions, when the wave electric field satisfies Ex 1 V/m, KAWs carry sufficient energy to offset energy losses in coronal loops. This suggests proton beams provide additional free energy to enhance KAW amplitudes, heating coronal loops more effectively.

Using test particle models, Malara et al. studied KAW turbulence energization of coronal electrons. KAW turbulence can stochastically accelerate electrons through parallel electric fields, raising their energy to hundreds of eV within tens to hundreds of seconds. The power absorbed by electrons from waves scales with the cube of large-scale velocity amplitudes, comparable to turbulent cascade power spectra. Singh et al. studied anisotropic KAW turbulence effects on coronal heating. As KAWs propagate, coherent structures collapse transversely, generating turbulence. The magnetic fluctuation power spectrum exhibits strong anisotropy in wavenumber space, indicating that nonlinear interactions redistribute energy among waves of different scales, causing KAW energy to cascade from large to small scales for dissipation.

3.3 KAW Heating Mechanism in Coronal Plumes

Coronal plumes are plasma structures formed in open magnetic field regions of coronal holes—dense, ray-like bright features with densities several times the coronal hole average. Plume widths are about 0.1 solar radii, but extend from the coronal base to over ten solar radii. Plume lifetimes range from several to tens of hours. Without confinement and heating mechanisms, coronal plumes would dissipate quickly and could not persist for such durations, yet their heating mechanism remains unclear. Figure 19 [Figure 19: see original paper] shows a semi-empirical radial model of a coronal hole, with panels displaying background plasma density n_0, electron temperature Te, magnetic field strength B_0, flow velocity vR, and electron plasma βe.

Figure 20 [Figure 20: see original paper] shows radial distributions of plasma parameters in coronal plumes, including resonant parameter αc, KAW dissipation rate , radiative loss rate QL, and required magnetic field strength $\delta B/B_0$ for KAW heating. At distances of 1.1-10 R in coronal plumes, the resonant condition satisfies αc 1, indicating that KAW Landau resonant interaction plays an important role in plume heating. In this region, the KAW dissipation rate $> 10^{-5}$, and the required magnetic field strength for heating satisfies δB $\leq 10^{-3} B_0$. This demonstrates that KAWs can effectively dissipate wave energy, converting it to particle thermal energy, and that the carried wave energy is sufficient to heat coronal plumes.

Based on a radial solar wind model for coronal holes, Wu et al. studied KAW wave-particle resonant interaction effects on electron heating in coronal plumes. The KAW heating rate is given by Q = (1 - nb/2nb)c^2UB, where UB = $|\delta By|^2/2\ _0$ represents magnetic energy density.

4. Summary

Alfvén waves are the most important low-frequency wave modes in magnetized plasmas and represent a crucial energy transport mechanism in solar and space plasma environments. Kinetic Alfvén waves are dispersive Alfvén waves with perpendicular wavelengths comparable to the ion gyroradius or electron inertial length. They play important roles in plasma particle heating, acceleration, and anomalous transport, and have been widely applied to explain observed phenomena such as non-uniform coronal heating, sunspot heating, coronal loop heating, and coronal plume heating. Consequently, KAW excitation and dissipation mechanisms in solar and space plasmas have attracted extensive interest and attention.

This review summarizes research progress on KAW excitation mechanisms and wave-particle interactions in the solar atmosphere. Common KAW excitation mechanisms include: proton/electron temperature anisotropy instability, field-aligned current instability, electron beam instability, density gradient instability, and resonant mode conversion. Key findings include: (1) Temperature anisotropy instabilities require relatively high plasma β for effective excitation, with electron temperature anisotropy being more effective than proton temperature anisotropy; (2) Field-aligned current instability is also an important mechanism. When drift velocity exceeds the Alfvén velocity, field-aligned currents can effectively excite KAWs, with growth rates and wavenumber ranges increasing with drift velocity; (3) Electron beam instability can effectively excite KAWs, with maximum growth rates occurring for drift velocities in the range $8 < vb/vA < 10$; (4) For density non-uniformity instability, strong density gradients are more favorable for KAW excitation. As the spatial scale of density non-uniformity kx/ $_0$ increases, the growth rate first increases then decreases. The maximum growth rate remains nearly constant as density amplitude n^*/n_0 increases; (5) In weakly density-non-uniform plasmas, Alfvén wave resonant mode conversion can effectively excite KAWs, with excitation strength sensitively depending on the angle α between density gradient and background magnetic field and on density gradient i. Proton beams can significantly enhance KAW amplitudes.

In the solar atmosphere, KAW dissipation affects energization phenomena including sunspot heating, coronal loop heating, and coronal plume heating. Key conclusions include: (1) For sunspot heating, acoustic waves effectively heat the photosphere and lower chromosphere, while KAWs more efficiently heat the upper chromosphere and corona; (2) For coronal loop heating, KAW Landau resonant dissipation depends sensitively on background magnetic field, enabling KAW heating rates in weak-field regions to exceed those in strong-field regions in some loops. The effective heating region at loop tops is larger than at footpoints, making KAW heating more effective at loop tops; (3) For coronal plume heating, KAWs can effectively dissipate wave energy through Landau resonant damping, converting wave energy to particle thermal energy and heating plumes.

From photosphere to corona, the likely heating processes are: acoustic wave neutral atom collisional dissipation in the photosphere and lower chromosphere; KAW electron-ion collisional dissipation in the upper chromosphere; and KAW Landau resonant damping in the transition region and corona. Currently, KAW heating mechanisms for the corona remain at the theoretical research stage. The successful launches of Parker Solar Probe and Solar Orbiter will provide local observations near the Sun, promising to advance our understanding of coronal heating mechanisms.

References

[1] Aschwanden M J, Poland A I, Rabin D M. ARA&A, 2001, 39: 175
[2] Aschwanden M J. *Physics of the Solar Corona: An Introduction with Problems and Solutions.* Berlin: Springer, 2004
[3] De Moortel I, Browning P. RSPTA, 2015, 373: 20140269
[4] Wu C S, Yoon P H, Wang C B. PhPl, 2015, 22: 032901
[5] Withbroe G L, Noyes R W. ARA&A, 1977, 15: 363
[6] Linsky J L. Recent Advances in Our Understanding of Chromospheric and Coronal Heating Mechanisms//Tuominen I, Moss D, Rüdiger G. *The Sun and*

Cool Stars: Activity, Magnetism, Dynamos. Berlin: Springer, 1991: 452-462
[7] Zhao K Y, Yang Z L. *Progress in Astronomy*, 2011, 29: 241
[8] Wang N H. *Progress in Astronomy*, 1996, 14: 204
[9] Biermann L. Z. Astrophys, 1948, 25: 161
[10] Schwarzschild M. ApJ, 1948, 107: 1
[11] Boynton G C, Torkelsson U. A&A, 1996, 308: 299
[12] Alfvén H, Lindblad B. MNRAS, 1947, 107: 211
[13] Cowling T G//Kuiper G P. *The Sun.* Chicago: University of Chicago, 1953: 532
[14] Piddington J H. MNRAS, 1956, 116: 314
[15] Wu D J. *Kinetic Alfvén Wave: Theory, Experiment, and Application.* Beijing: Science Press, 2012
[16] Wu D J, Chen L. *Kinetic Alfvén Waves in Laboratory, Space, and Astrophysical Plasmas.* Nanjing: Nanjing University Press, 2021
[17] Lysak R L, Lotko W. JGRA, 1996, 101: 5085
[18] Hollweg J V. JGRA, 1999, 104: 14811
[19] Cramer N F. *The Physics of Alfvén Waves.* Berlin: Wiley-VCH, 2001
[20] Cross R. *An Introduction to Alfvén Waves.* England: IOP Publishing, 1985
[21] Chen L, Wu D J. PhPl, 2011, 18: 072110
[22] Liu D J, Chen L. PhyS, 2011, 84: 025506
[23] Chen L, Hasegawa A. PhFl, 1974, 17: 1399
[24] Chen L, Hasegawa A. JGR, 1974, 79: 1033
[25] Hasegawa A, Chen L. PhRvL, 1975, 35: 370
[26] Hasegawa A, Chen L. PhFl, 1976, 19: 1924
[27] Goertz C K, Boswell R W. JGRA, 1979, 84: 7239
[28] Wu D J. CoTPh, 2003, 39: 457
[29] Tomczyk S, McIntosh S W, Keil S L, et al. Science, 2007, 317: 1192
[30] Jess D B, Mathioudakis M, Erdélyi R, et al. Science, 2009, 323: 1582
[31] McIntosh S W, De Pontieu B, Carlsson M, et al. Nature, 2011, 475: 477
[32] Woo R. Nature, 1996, 379: 321
[33] Woo R, Habbal S R. ApJ, 1997, 474: L139
[34] Wu D J, Huang J, Tang J F, et al. ApJ, 2007, 665: L171
[35] Klimchuk J A. RSPTA, 2015, 373: 20140256
[36] Schmelz J T, Winebarger A R. RSPTA, 2015, 373: 20140269
[37] Yoon P H, Wu C S, De Assis A S. PhFlB, 1993, 5: 1971
[38] Chen L, Wu D J. PhPl, 2010, 17: 062107
[39] Malovichko P, Voitenko Y, De Keyser J. ApJ, 2014, 780: 114
[40] Chen L, Wu D J, Huang J. JGRA, 2013, 118: 2951
[41] Chen L, Wu D J. ApJ, 2012, 754: 123
[42] Chen L, Wu D J, Hua Y P. PhRvE, 2011, 84: 046406
[43] Voitenko Y M. SoPh, 1998, 182: 411
[44] Chen L, Wu D J, Zhao G Q, et al. ApJ, 2014, 793: 13
[45] Duan S P, Li Z Y. ChA&A, 2005, 29: 1
[46] Duan S P, Li Z Y, Liu Z X. P&SS, 2005, 53: 1167
[47] Wu D J, Chen L. ApJ, 2013, 771: 3
[48] Chen L, Wu D J, Zhao G Q, et al. JGRA, 2015, 120: 61

[49] Sridhar S, Goldreich P. ApJ, 1994, 432: 612
[50] Goldreich P, Sridhar S. ApJ, 1995, 438: 763
[51] Goldreich P, Sridhar S. ApJ, 1997, 485: 680
[52] Voitenko Y, Goossens M. SoPh, 2002, 209: 37
[53] Shukla P K, Stenflo L. Nonlinear Phenomena Involving Dispersive Alfvén Waves//Passot T, Sulem P L. *Nonlinear MHD Waves and Turbulence*. Berlin: Springer, 1999: 1-34
[54] Kletzing C A. JGRA, 1994, 99: 11095
[55] Stasiewicz K, Bellan P, Chaston C, et al. SSRv, 2000, 92: 423
[56] Liang J, Lin Y, Johnson J R, et al. JGRA, 2016, 121: 6518
[57] Dai L, Wang C, Zhang Y C, et al. GeoRL, 2017, 44: 634
[58] Shukla A, Sharma R P. JASTP, 2002, 64: 661
[59] Rudakov L, Mithaiwala M, Ganguli G, et al. PhPl, 2011, 18: 012307
[60] Sharma R P, Kumar S. JPlPh, 2010, 76: 239
[61] Isenberg P A, Vasquez B J. ApJ, 2019, 887: 63
[62] Gary S P, Montgomery M D, Feldman W C, et al. JGR, 1976, 81: 1241
[63] Quest K B, Shapiro V D. JGRA, 1996, 101: 24457
[64] Yoon P H. PhyS, 1995, 1995: 127
[65] Melrose D B. SoPh, 1990, 130: 3
[66] Klein K G, Verniero J L, Alterman B, et al. ApJ, 2021, 909: 7
[67] Voitenko Y, Goossens M. SSRv, 2003, 107: 387
[68] Wiegelmann T, Petrie G J D, Riley P. SSRv, 2017, 210: 249
[69] Chaston C C, Carlson C W, Peria W J, et al. GeoRL, 1999, 26: 647
[70] Xiang L, Chen L, Wu D J. ApJ, 2019, 881: 61
[71] Xiang L, Chen L, Wu D J, et al. ApJ, 2022, 936: 159
[72] Gabriel A H. RSPTA, 1976, 281: 339
[73] Avrett E H//Cram L E, Thomas J H. *The Physics of Sunspots*. New Mexico: SPO, 1981: 235-255
[74] Ding M D, Fang C. A&A, 1989, 225: 204
[75] Ding M D, Fang C. *Acta Astronomica Sinica*, 1990, 31: 276
[76] Wu D J, Fang C. ApJ, 2007, 659: L181
[77] Bray R J, Cram L E, Durrant C, et al. *Plasma Loops in the Solar Corona*. Cambridge: Cambridge University Press, 1991: 522
[78] Porter L J, Klimchuk J A. ApJ, 1995, 454: 499
[79] Wu D J, Fang C. ApJ, 1999, 511: 958
[80] Malara F, Nigro G, Valentini F, et al. ApJ, 2019, 871: 66
[81] Singh H D, Jatav B S. RAA, 2019, 19: 185
[82] Widing K G, Feldman U. ApJ, 1992, 392: 715
[83] Walker Jr A B C, Deforest C E, Hoover R B, et al. SoPh, 1993, 148: 239
[84] Wang Y M. ApJ, 1994, 435: L153
[85] Wang Y M, Sheeley Jr N R. ApJ, 1995, 452: 457
[86] Wu D J, Fang C. ApJ, 2003, 596: 656
[87] Alfvén H. Nature, 1942, 150: 405
[88] Galeev A A, Sagdeev R Z. Ap&SS, 1988, 144: 427

Note: Figure translations are in progress. See original paper for figures.