Transverse Oscillations and Novel Energy Source in a Strongly Magnetized Sunspot

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Transverse Oscillations and Novel Energy Source in a Strongly Magnetized Sunspot

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The solar corona is maintained at a temperature of millions of Kelvin, 2 to 3 orders of magnitude hotter than the underlying photosphere. The plasma above sunspots is fully ionized and is subjected to a strong energy loss in form of radiation and thermal conduction. An heating flux above $1,000\,\mathrm{Wm^{-2}}$ is required to maintain the plasma temperature at coronal level[1]. Repetitive magnetic energy releases at short length scales, known as nanoflares, is proposed as one of the potential heating mechanisms, however, no persuasive observation has even been reported yet[2,3]. Magnetotohydrodynamic (MHD) waves do not display promising plasma heating efficiency, because they are observed to either have strong energy flux with low occurrence rate or the otherwise[4–8]. Using the Goode Solar Telescope, we report a first detection of ubiquitous and persistent transverse waves in umbral fibrils within a strongly magnetized sunspot. The energy flux carried by these kink waves were estimated to be about $7.52 \times 10^{6}\,\mathrm{Wm^{-2}}$, 3 to 4 orders of magnitude stronger than the required energy flux to compensate the energy losses in the active region. Two-fluid MHD simulation reproduced the novel observations and showed that these transverse waves could dissipate a significant amount of energy indispensable for coronal heating. Our study identifies a novel source in forms of MHD waves that could provide sufficient energy flux for coronal heating.

The dissipation of direct current and self-reorganization of complex magnetic fields, also known as magnetic reconnection, would result in energy transients at a diversity of spatio-temporal scales in the solar atmosphere. The associated energy release is believed to the main trigger of plasma heating and eruptions[2,3,9–12]. The magnetic fields anchored in the convection zone are laden with ionized plasma, and they act as waveguides for MHD waves, such as Alfvén, fast and slow magnetoacoustic modes. These waves have the potential to provide energy to heat solar plasma to coronal temperatures.[4–8,13,14] Slow magnetoacoustic waves are ubiquitously detected in sunspots and open coronal loops, however, the associated energy flux is too weak for plasma heating. They are mainly used for plasma diagnostics and are considered as the potential source for solar wind.[15–17] Fast magnetoacoustic waves normally carry a strong energy flux, however, the energy transportation and dissipation mechanisms are still poorly understood in both theory and observation,[18,19] Moreover, the fast waves are usually driven by explosive events, the occurrence rate is too low to maintain the plasma temperature at millions of Kelvin[14]. Alfvén waves could carry a strong energy flux and could dissipate the energy with high efficiency, however, as Alfvén waves usually do not perturb the plasma density[20], they could not be directly observed with optical instruments.[4,5,20]

A substantial amount of energy flux may be associated with various wave modes in the magnetized solar atmosphere. However, an enigma is how the energy is transported and dissipated in the highly structured solar atmosphere.[4–8,13,14,21,22] The physical behaviour of the lower solar atmosphere affects severely the understanding of wave energy propagation and dissipation[13], however, there might be possible observational constraints that hide a significant portion of wave energy as a “dark energy”.[23,24] In this paper, we present a first observation of transverse waves in a strongly magnetized sunspot using the high-resolution observations and the estimation of key parameters of the transverse MHD waves. We also compute the wave energy flux by applying a cutting-edge Stoke's inversion method and an stringent analytic model of the kink MHD waves. We reproduce the excitation, propagation, and energy dissipation of the kink MHD waves in a two-fluid MHD simulation. We thereby provide a novel scenario for energy transfer in a sunspot with strong magnetic field, which connects the photosphere, chromosphere, and corona, and therefore, act as an effective channel for pumping up the dynamic energy from the sub-photosphere to the upper atmosphere.

The Visible Imaging Specctrometer (VIS) installed in Goode Solar Telescope at Big Bear Solar Observatory[25] (BBSO) performed high-resolution observations on sunspot AR12384 (see Figure 1). The observations started on 17:36:26 UT and stopped at 18:06:26 UT on 14th July, 2015. The sampling interval was about 19 s, whereas the spatial resolution was 0.029″/pixel, or about 22 km per pixel (see the details in Appendix-I). The sunspot region was scanned by VIS tuned at the H_α 6563 Å line. The scanning spanned over the blue wing (-1.0 Å) to the red wing (1.0 Å) with a step of 0.2 Å. Each image was reconstructed by the Speckle imaging techniques[26]. This method removed pointing errors introduced by the turbulence in Earth's atmosphere, and thus rendered the observational data set well suitable for capturing the fine plasma dynamics at sub-arcsec spatial scale (see Figure 1b and 1c).

Within the sunspot's umbra, numerous dark features were prominently detected. They usually had an irregular and compact shape, and occupied $29\% \sim 33\%$ of the umbra area (see Figure 1and Supplementary Video 1). These features are fibrils aligned with the nearly vertical mag-

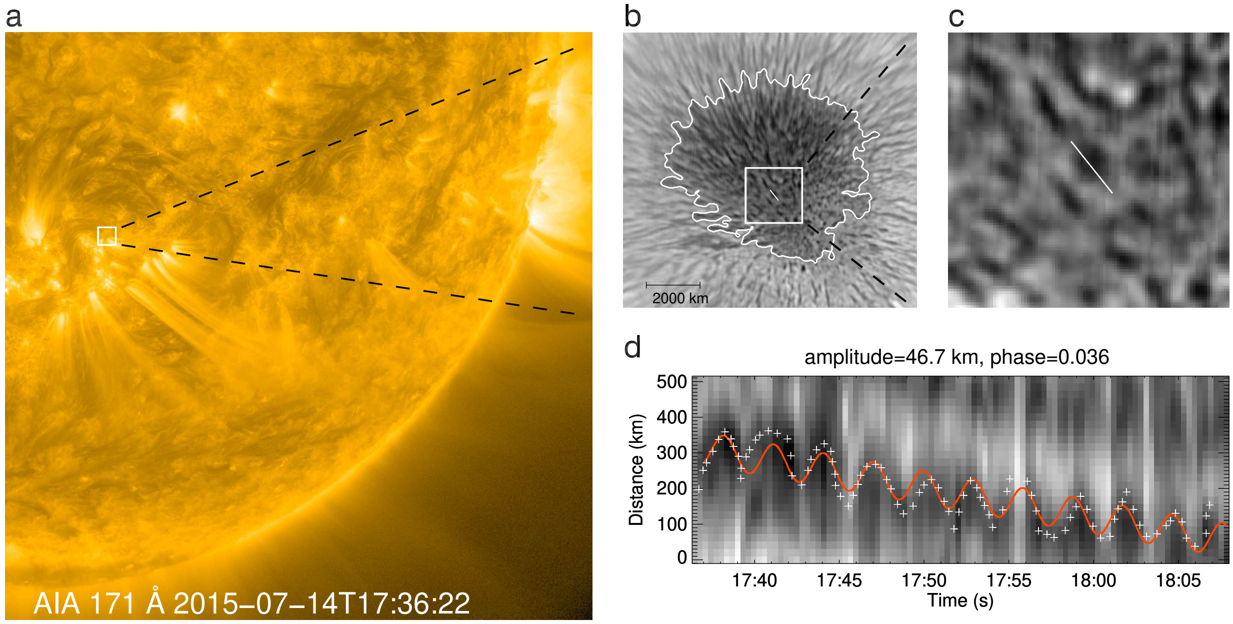

Figure 1: Oscillatory transverse motion of the dark fibril within the sunspot (Supplementary Video 1). (a) AIA 17 Å image showing the active region AR 12384 on 14 July, 2015. (b)-(c) $\mathrm{H}_\alpha - 0.20$ Å image showing the sunspot in AR 12384. Its zoomed view highlights the dark fibrils and the slit used to track inherent transverse motions. (d) Time-distance plot revealing the transverse oscillations. The plus sign marked the fibril's position, where the red curve is a fitting of a sinusoidal function and a liner trend.

netic field lines. The fibrils usually have a greater density and elevated formation heights.[27] In order to maintain the balance of total pressure (a sum of magnetic and gas pressures), the fibrils should have a lower temperature, therefore, they could be the coldest structures ever detected on the Sun (see Figure 1c). They were detectable in several bandpasses: H_α line core, $\mathrm{H}_\alpha \pm 0.2\,\text{Å}$, and $\mathrm{H}_\alpha \pm 0.4\,\text{Å}$. We only used the $\mathrm{H}_\alpha + 0.2\,\text{Å}$ data set for further analysis in this paper.

A sunspot usually has a strongly vertical magnetic component at a few kilo Gauss. The magnetic pressure in a spot is much greater than the gas pressure, therefore, plasma motions do not drive lateral motion in the magnetic field. A sunspot is an optimal waveguide for the slow waves, which only perturb plasma motions along the magnetic field lines,[28] while the gas pressure is a few orders of magnitude smaller than the magnetic pressure in sunspots. Therefore, these slow waves do not transport sufficient energy flux to the overlying atmosphere.[14]

In this study, we observed for the first time transverse oscillations across magnetic field lines in the umbra of sunspot AR12384, which had a magnetic field strength up to $4000\,\mathrm{G}$. Figure 1d depicts a representative case. We placed an artificial slit normal to an oscillating fibril (see Figure 1c), and traced the lateral motions of the fibril. We used the $\mathrm{H}_\alpha + 0.2\,\text{Å}$ images to make this measurement. The image were cropped to a smaller field-of-view (FOV) centered at the sunspot in AR12384, and then, they were aligned to a sub-pixel accuracy. The emission intensity along the slit across the fibril was stacked in order of collapsing time to make a time-distance map. The transverse motion was tracked manually, and the uncertainty was assumed to be one pixel (or equivalently $22\,\mathrm{km}$). The transverse motion was subsequently fitted with a sinusoidal function, then we obtained the oscillation amplitude and period (see Appendix-I). The exemplary fibril presented in Figure 1 oscillated with a period of $176.4 \pm 1.75\,\mathrm{s}$ and an displacement amplitude of $46.9 \pm 9.88\,\mathrm{km}$. We analyzed the transverse oscillation of eight fibrils. The average oscillation period was $240 \pm 32.8\,\mathrm{s}$, and the displacement amplitude $43.8 \pm 13.9\,\mathrm{km}$. The oscillation parameters are listed in Table A1.1 of Appendix-I.

These fibril oscillations had a significant transverse displacement perpendicular to the magnetic field of the umbra. This is a feature of kink waves trapped within a magnetic flux tube.[29,30] This is the first report that kink waves are observed in kilo-Gauss magnetised umbra of a sunspot. Such transverse waves are traditionally observed in active region coronal loops, which have a magnetic field strength of about 10 to 100 Gauss and a density of 4 to 6 orders of magnitude smaller than that of a sunspot. The energy flux carried by these kink waves in coronal loop is not sufficient to compensate the energy loss of the coronal plasma.[14]

The intriguing fact of this observation is that the transverse oscillations were detected in colder and denser magnetic flux tubes rooted in the umbral region of a sunspot, where the magnetic field strength could reach thousands of Gauss. No significant damping was detected within these transverse oscillations, which implies that these waves were continuously driven by a periodic source in the umbral region of the sunspot. The transverse waves detected in this study could significantly perturb the magnetic field at the order of a few hundreds Gauss, therefore they must carry a substantial amount of energy to the upper atmosphere. These waves continuously pump energy from the sunspot to the plasma confined in overlying large-scale coronal loops. In this sce-

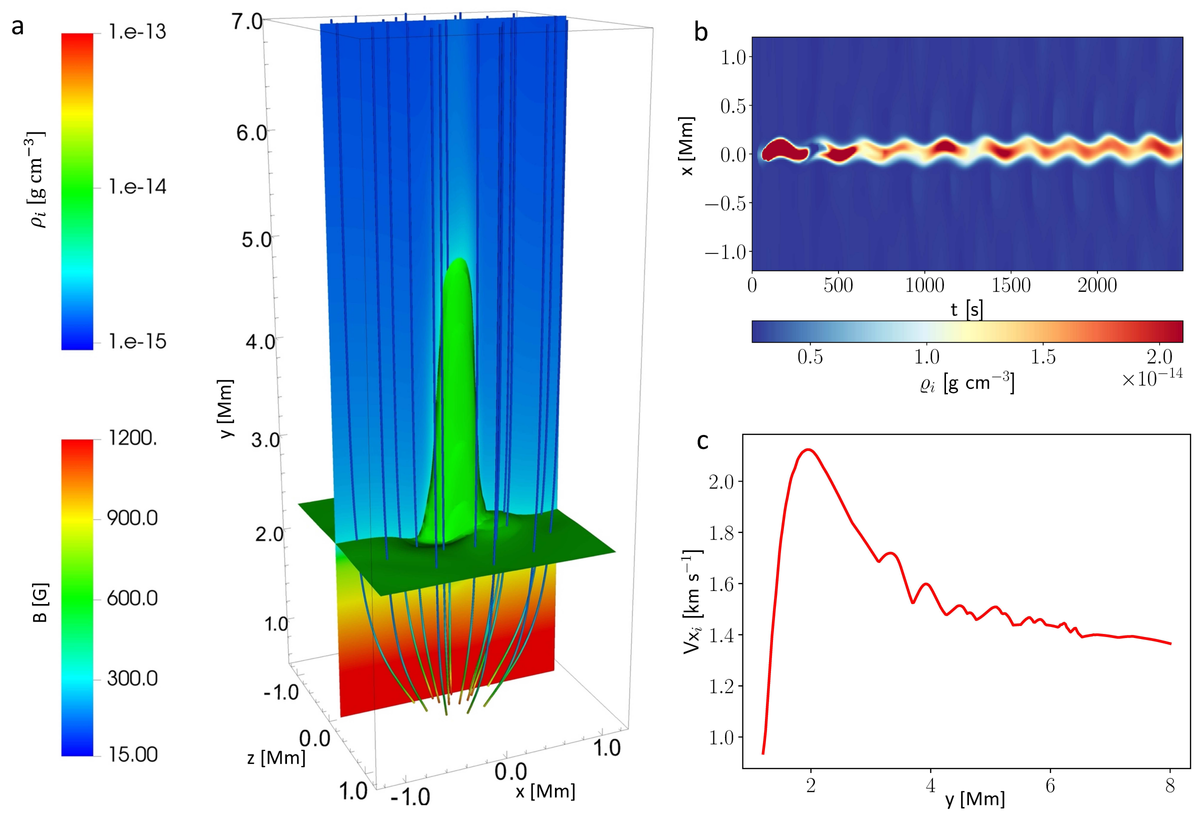

Figure 2: Numerical simulation of driven propagating fast magnetoacoustic wave (Supplementary Video 2). (a) A 3D structure of the magnetic field lines, the stratified sunspot atmosphere in terms of ion mass density, and the initial simulated fibril structure. (b) A horizontal cut at the fibril center revealing the driven transverse motion. (c) Oscillation amplitude in ion velocity as a function of height.

nario, we conjecture that active region coronal loops oscillate persistently with larger amplitudes, as their magnetic field strength and density is much lower than that of the underlying sunspot. However, in reality, the coronal loops only oscillate after solar flare and are damped after a few oscillation cycles,[31,32] or the oscillations had very small amplitude, eventually known as decay-less transverse oscillations[33], and are detected only after amplification of the motion. Therefore, we infer that in present case the wave energy flux is either dissipated or reflected by the inhomogeneity of magnetic field and density within this sunspot. In either case, the persistent transverse oscillations were kink waves propagating in fibrils and carried a strong energy flux, which has to be released in form of solar wind or nanoflares to cause subsequent dynamical plasma processes and heating.

In order to demonstrate the kink wave propagation in magnetic fibrils and the associated energy transportation, we performed a 3D two-fluid MHD simulation of sunspot dynamics. The numerical sunspot atmosphere included the photosphere, chromosphere, transition region, and corona, and was permeated of a diverging kilo-Gauss magnetic field (see Figure 2a, Supplementary Video 2, and Appendix-II). To generate a cold and dense umbral fibril, we added a vertical slender region with enhanced pressure in the ambient equilibrium atmosphere, which is given by

$$p_{\alpha} = p_{0\,\alpha}\left(1 + A_p \exp\left(-\frac{x^2 + (y - y_0)^2 + z^2}{w^2}\right)\right). \quad (1)$$

Here α stands either for ions (i) or for neutrals (n). A periodic transverse driver was operated at the bottom boundary of the model fibril,

$$v_{x_\alpha} = A_{v_x} \exp\left(-\frac{x^2 + (y - y_0)^2 + z^2}{w^2}\right) \sin\left(\frac{2\pi}{P_{\mathrm{d}}} t\right). \quad (2)$$

This driver could generate an upwardly propagating kink wave. The parameters were setup to mimic the average observational values, $A_p = 100$ (the pulse amplitude), $A_{v_x} = 5\,\mathrm{km \cdot s^{-1}}$ (the velocity perturbation), $w = 50\,\mathrm{km}$ (the width of the pulse), and $P_d = 240\,\mathrm{s}$ (the period of the driver).

The simulated fibril had a length varying between $2000\,\mathrm{km}$ and $5000\,\mathrm{km}$ and an average width of about $100\,\mathrm{km}$ (Figure 2a), and it exhibited a periodic transverse displacement (Figure 2b). This periodic motion is a pattern of trapped fast wave in the magnetic flux tube (the fibril). This kink wave was driven by the periodic lateral displacement at the bottom boundary, and it was guided by the fibril structure—a denser region with lower Alfvén speed. This fibril oscillated with a period of $240\,\mathrm{s}$, close to the period of the driver. The displacement amplitude of this guided kink wave varied with the height, but closely matched with the observed values (about $50\,\mathrm{km}$). Figure 2c draws the ion velocity amplitude of the kink wave as a function of height. It shows clearly that the velocity amplitude was about $1.0\,\mathrm{km \cdot s^{-1}}$ at the middle chromosphere ($y = 1.0\,\mathrm{Mm}$). It increased with height and reached a maximum value ($\approx 2.1\,\mathrm{km \cdot s^{-1}}$) at a height of $y = 2.1\,\mathrm{Mm}$ at the top of chromosphere. Thereafter, the velocity amplitude started to drop off to $\approx 1.4\,\mathrm{km \cdot s^{-1}}$ as the wave reached the transition region and corona ($y > 2.1\,\mathrm{Mm}$). The velocity amplitude was consistent with the observed average amplitude of $\approx 1.4\,\mathrm{km \cdot s^{-1}}$ (see Table A1.1 in Appendix-I). The initial growth of the wave amplitude was associated with the density decrease with height, and this trend competed with the energy dissipation caused by ion-neutral collisions in the chromosphere[34]. The kink wave energy partially leaked laterally to the ambient plasma in the chromosphere and transition region, and a proportion is transmitted to the inner corona (see Figure 2b and Appendix-II).

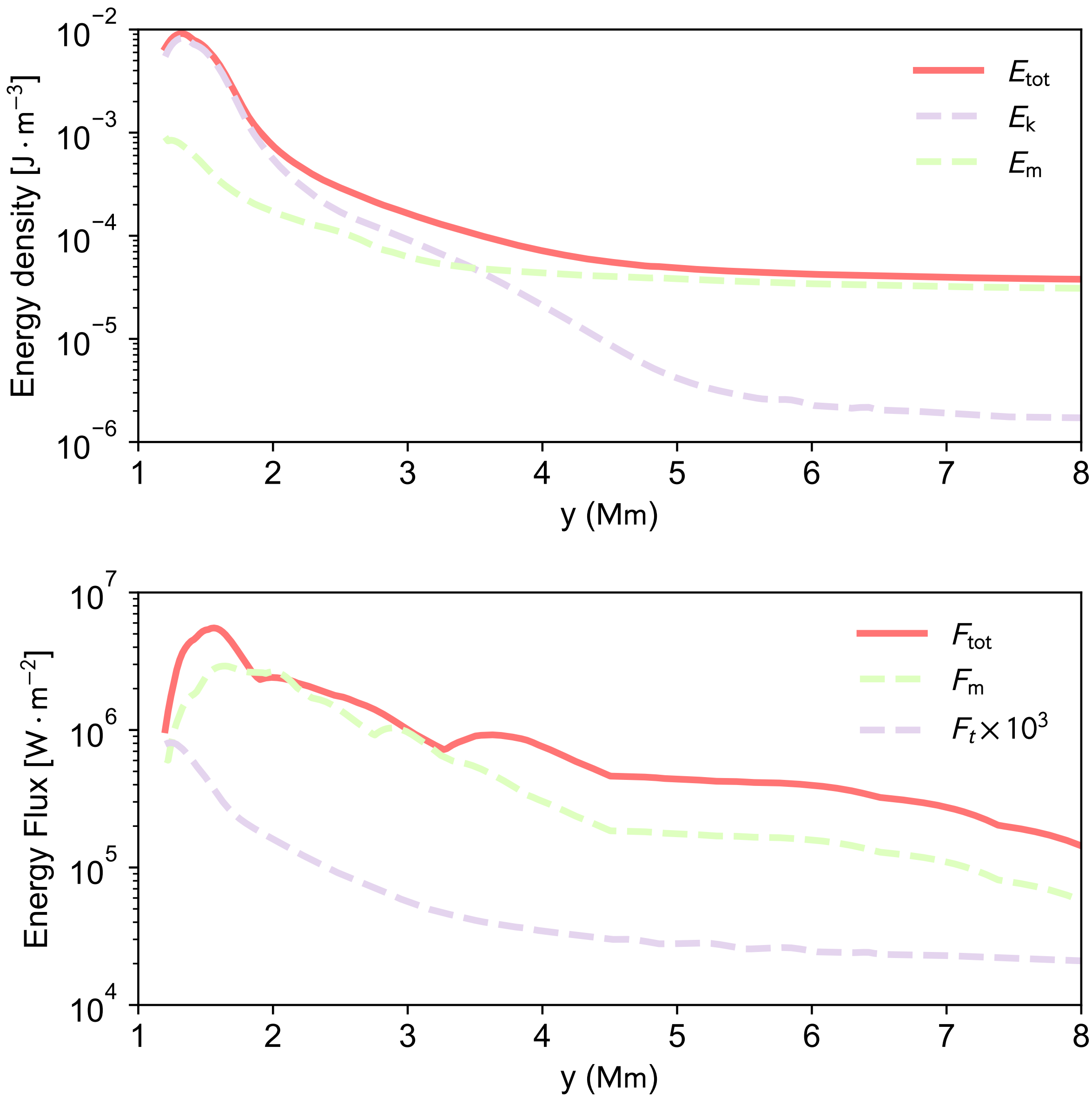

Figure 3: Energy densities and fluxes carried by the fast kink wave in the simulation. (a) Kinetic ($E_{\rm k}$), magnetic($E_{\rm m}$), and total($E_{\rm tot}$) energy density as a function of height. (b) Thermal ($F_{\rm t}$), magnetic($F_{\rm m}$), and total ($F_{\rm tot}$) energy fluxes in the oscillating fibril. The thermal energy flux is amplified by a factor of 1000 for visualization purpose.

Our observation and two-fluid MHD simulation reveal for the first time that fast kink wave is excited in the lower atmosphere of a sunspot, and cause transverse displacement of umbral fibrils in a strong magnetic field. The energy carried by these MHD waves could be a novel energy reservoir and trigger many other energetic processes in a sunspot and the overlaying active region. We now estimate the total energy flux carried by these fast kink waves. As direct measurement of the plasma parameters are not possible with modern instrumentation, we used the Stokes observed by the Near-Infrared Imaging Spectro-polarimeter (NIRIS) at BBSO and used Stokes Inversion based on Response functions (SIR) code to calculate magnetic field, plasma density and temperature for the various optical depths (see Appendix-III). A fast kink MHD wave model in a magnetized plasma cylinder was developed (see Appendix-IV for details) to calculate the energy flux. The energy flux is calculated by integrating over the magnetic flux and the ambient plasma and averaged over one wave cycle, and the filling factor was set to 0.31 in accordance with the fraction of umbral area filled with fibrils. The total energy flux along the vertical direction was estimated to be about $7.5 \times 10^6\,\mathrm{W}\cdot\mathrm{m}^{-2}$, this part transfers energy upwards and acts as a plasma heating flux. The fractions of the Poynting (magnetic) and thermal energy fluxes are listed in Table A4.1 in Appendix-IV. Figure 3 presents the energy density and energy flux in the oscillatory fibril in the simulation, the estimated peak energy flux reaches $6.6 \times 10^6\,\mathrm{W}\cdot\mathrm{m}^{-2}$ at $y = 1.6\,\mathrm{Mm}$ and drops to about $2 \times 10^5\,\mathrm{W}\cdot\mathrm{m}^{-2}$ at $y = 8\,\mathrm{Mm}$. In both the observation and simulation, we obtained a very strong energy flux directed to the solar corona, and act as an important clue to the coronal heating dilemma.

In this study, we used high-resolution observations provided by the GST, and observed for the first time that dark fibrils within a sunspot's umbra oscillated transversely across strong magnetic field of kilo Gauss level. These transverse oscillations as basically fast kink mode waves trapped within vertically elongated fibrils. In order to calculate the energy density and flux carried by these waves, we developed an analytic model for a plasma cylinder, and derived formulas for the energy densities and fluxes. The parameters of the plasma and magnetic field within the sunspot were obtained by Stokes inversion. We found that the energy flux carried by these kink waves were 3 to 4 orders of magnitude stronger than the required energy flux for active region plasma heating. This flux is permanently directed to the upper atmosphere, but were attenuated as they reach the corona as demonstrated by two fluid MHD simulations.

In summary, this paper identifies a novel and important energy source in a strongly magnetic sunspot with the high resolution observation. The analytic calculation and numerical simulation demonstrate that this energy source could transport an energy flux well above the required heating rate for active region plasma. The study significantly advances our understanding of coronal plasma heating by MHD waves. Continuously driven fast kink MHD waves could be potentially found in other magnetic structure of the sun, such as coronal hole, pore and open coronal loops, and they could play an important role in heating the corona in general.

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Competing Interests The authors declare that they have no competing financial interests.

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Author's Contributions DY made the initial discovery, conceived the scientific research, analyzed the data, and summarized the manuscript. WDC operate the instruments and generated the observational data. LBF, YHM, SF, and JTS contributed to data analysis. BK and KM developed the numerical model and analyzed the numerical data. MG and TVD developed the analytic model. JTA, CQN, and BRC did the Stokes inversion of NIRIS observation. AKS contributed in the scientific work and writing of the manuscript.

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Data Availability Statement The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.

List of On-line Materials **Author Information**

Data Availability Statement:

The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.

List of On-line Materials:

(i) Online-Appendix-I: Data Analysis and Kinetic Study

(ii) Online-Appendix-II: Two-Fluid MHD Modelling of a Kink Wave in a Sunspot

(iii) Online-Appendix-III: Observation and Inversion of Stokes Parameters

(iv) Online-Appendix-IV: Energy Flux Estimation of the Oscillating Fibrils in a sunspot

(v) Supplementary Video 1: Video showing the high-resolution observations of the representative transverse motion in the sunspot.

(vi) Supplementary Video 2: Video showing the transversely oscillating fibril in two-fluid MHD simulation.

Supplementary Files

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