HINODE AND IRIS OBSERVATIONS OF THE MAGNETOHYDRODYNAMIC WAVES PROPAGATING FROM THE PHOTOSPHERE TO THE CHROMOSPHERE IN A SUNSPOT

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ABSTRACT

Magnetohydrodynamic (MHD) waves have been considered as energy sources for heating the solar chromosphere and the corona. Although MHD waves have been observed in the solar atmosphere, there are a lack of quantitative estimates on the energy transfer and dissipation in the atmosphere. We performed simultaneous Hinode and Interface Region Imaging Spectrograph observations of a sunspot umbra to derive the upward energy fluxes at two different atmospheric layers (photosphere and lower transition region) and estimate the energy dissipation. The observations revealed some properties of the observed periodic oscillations in physical quantities, such as their phase relations, temporal behaviors, and power spectra, making a conclusion that standing slow-mode waves are dominant at the photosphere with their high-frequency leakage, which is observed as upward waves at the chromosphere and the lower transition region. Our estimates of upward energy fluxes are 2.0 \times 10^7 \text{erg cm}^{-2} \text{s}^{-1} at the photospheric level and 8.3 \times 10^4 \text{erg cm}^{-2} \text{s}^{-1} at the lower transition region level. The difference between the energy fluxes is larger than the energy required to maintain the chromosphere in the sunspot umbrae, suggesting that the observed waves can make a crucial contribution to the heating of the chromosphere in the sunspot umbrae. In contrast, the upward energy flux derived at the lower transition region level is smaller than the energy flux required for heating the corona, implying that we may need another heating mechanism. We should, however, note a possibility that the energy dissipated at the chromosphere might be overestimated because of the opacity effect.

Key words: Sun: chromosphere – Sun: corona – Sun: magnetic fields – Sun: oscillations – Sun: photosphere

1. INTRODUCTION

Thermal conduction from the solar interior cannot form the solar outer atmosphere, i.e., the chromosphere and the corona, and thus a nonthermal mechanism is required. Magnetohydrodynamic (MHD) waves have been considered as one of the candidates for the mechanism of the energy transfer to the outer atmosphere. The waves are excited by interactions between magnetic field lines and convective gas flows at the photosphere. They propagate upward along the magnetic field lines, followed by the dissipation of the energy in the upper atmosphere. Depending on the wave modes, frequency, and field topology, a fraction of the waves may reflect back to the lower atmospheric layers.

Compressible magnetoacoustic waves may be evolved to shock waves due to steepening, and their dissipation might contribute to the heating of the atmosphere. The temporal profiles of the Doppler velocity measured at the chromosphere show the sawtooth shapes, and they can be a signature of the shock formation (Rouppe van der Voort et al. 2003; Centeno et al. 2006; Tian et al. 2014). They also reported intensity enhancements with blueshifted motion, indicating the strong compression and heating at the shock front. However, magnetoacoustic waves generated at the photosphere are thought to be an insufficient driver to heat the solar corona because of rapid dissipation before reaching the corona (Mein & Schmieder 1981; Anderson & Athay 1989). Therefore, such waves are currently considered as a possible candidate for heating the chromosphere, and we need further quantitative evaluations and discussions.

Alfvén waves are waves in incompressible modes and thus have difficulty evolving to the shock waves and dissipating the energy, compared to the compressible waves. Therefore, they may carry much energy to the corona without dissipating before reaching the corona. The Coronal Multi-Channel Polarimeter, Hinode (Kosugi et al. 2007), and the Atmospheric Imaging Assembly (Pesnell et al. 2012) on board the Solar Dynamics Observatory (Pesnell et al. 2012) found that the solar atmosphere is filled with Alfvén waves. Tomczyk et al. (2007) provided the time series of the line-of-sight (LOS) velocity, the intensity, and the linear polarization maps measured with CoMP, revealing propagating oscillatory signals in large-scaled coronal structures. By using the Solar Optical Telescope (SOT; Ichimoto et al. 2008; Shimizu et al. 2008; Suematsu et al. 2008; Tsuneta et al. 2008) on board Hinode, Okamoto et al. (2007) and De Pontieu et al. (2007) found transverse oscillations in the chromospheric prominences and spicules, suggesting the existence of Alfvén waves. By using the Extreme Ultraviolet Imaging Spectrometer (Culhane et al. 2007) on board Hinode, Hahn et al. (2012) and Hahn & Savin (2013) reported the decrease in the nonthermal line widths with heights in the polar coronal hole and suggested a signature for the energy dissipation of Alfvén waves. More recently, the Interface Region Imaging Spectrograph (IRIS; De Pontieu et al. 2014), coordinated with the Hinode/SOT, provided a spectroscopic measurement of oscillations in chromospheric prominence threads, suggesting the resonant absorption of Alfvén waves and their subsequent heating (Antolin et al. 2015; Okamoto et al. 2015).
The MHD waves are dominantly generated by the photospheric motions, and the linkage between the photospheric motions and behaviors at the upper atmosphere is quite important for understanding the heating in the chromosphere and corona. Centeno et al. (2009) studied the MHD waves in the photosphere and the chromosphere by examining the simultaneous photospheric Si I line and chromospheric He I line obtained by the Tenerife Infrared Polarimeter (TIP) operating at the Vacuum Tower Telescope (VTT). They reported a variety of the chromospheric oscillations in amplitude, frequency, and stage of shock formation even when quite similar oscillations were observed at the photosphere, implying the importance of the propagating processes related to the magnetic features. Felipe et al. (2010) studied the waves in sunspots with He I λ10830, Ca II H λ3969, Fe I λ3969.3, Fe I λ3966.6, Fe I λ3966.1, Fe I λ3965.4, and Si I λ10827, covering the photosphere and the chromosphere. With the phase difference spectra of LOS velocities between several pairs of lines, they revealed standing waves at frequencies lower than 4 mHz and a continuous propagation of waves at higher frequencies, which is consistent with the slow-mode waves in the stratified atmosphere. Similar results are reported by Centeno et al. (2006) and Kobanov et al. (2013). Felipe et al. (2011) performed the data-driven MHD simulation of the waves in the sunspot and reported a remarkable agreement with the observations.

The connectivity between the photospheric motions and the coronal response is also studied. Matsumoto & Shibata (2010) derived the spectrum of the photospheric horizontal velocity from the time series of Hinode’s G-band images and applied it to their MHD simulation. They found that the Alfvén waves excited by the observed photospheric granular motions can bring enough energy to the corona for the heating. Katsukawa & Tsuneta (2005) identified that the footpoints of the hot coronal loops have a lower magnetic filling factor than the footpoints of the cool coronal loops, indicating the importance of the flexibility in the photospheric horizontal motions to heat the corona.

An important observational study for understanding the roles of MHD waves in heating the upper atmosphere is to evaluate how much energy the observed MHD waves have at various atmospheric heights. Accurate measurements of physical quantities in the waves are required for the quantitative evaluation. MHD waves can give fluctuations to the magnetic fields, which observers have attempted to measure with ground-based telescopes (Landgraf 1997; Lites et al. 1998; Bellot Rubio et al. 2000). These observations, however, may not confidently show that the observed magnetic fluctuations are intrinsic because of the temporal fluctuations of the atmospheric seeing. Observations from space would provide more confident results. Fujimura & Tsuneta (2009) investigated the weak fluctuations in temporal behaviors of spectropolarimetric data from the Hinode/SOT, suggesting that the phase relations of the photospheric fluctuations in plages and pores can be explained by the dominant existence of standing waves at the photosphere with a small but sufficient leakage toward the chromosphere. It is worth noting that Fujimura & Tsuneta (2009) used only the photospheric information.

The fundamental motivation of this study is to estimate the dissipated energy of MHD waves in the upper atmosphere with simultaneous multi-height observations. The temporal behaviors of the physical parameters are important for identifying the mode of waves. The time series of the data obtained with ground-based telescopes are less suitable because of the seeing effect. Moreover, rather than imaging observations, spectroscopic observations are preferable for detecting the fluctuations caused by MHD waves in physical quantities quantitatively and accurately. For these reasons, the coordinated Hinode and IRIS observations are used in this study. Hinode’s spectropolarimetric observations provide tiny fluctuations in the physical parameters, including the magnetic flux density at the photospheric level, while the IRIS spectroscopic observations provide the temporal series of intensity and Doppler speeds measured with the chromospheric and the transition region spectral lines. The combination of these observations allows us to trace the temporal behaviors of MHD waves at the two atmospheric layers at the same time. As shown in Figure 1, the dissipation rate of the energy can be evaluated with the upward energy fluxes estimated at the two layers.

This paper presents a set of Hinode and IRIS simultaneous high-cadence observations and discusses how much energy flux the MHD waves observed in the data have at the two layers. The time series of the Hinode data used in the study has a cadence more than two times higher than that used in Fujimura & Tsuneta (2009), giving a more valid conclusion of the wave-mode identification. We describe observational methodologies in Section 2. Section 3 shows the observational results, which are interpreted and used for the estimate on the energy flux in Section 4. A summary of this paper and conclusions are given in Section 5.

2. OBSERVATIONS AND DATA ANALYSIS

Hinode and IRIS observed a well-developed leading sunspot of NOAA Active Region (AR) 11836 on 2013 September 4. The sunspot was located at $(x, y) = (510^\circ, 75^\circ)$ at 16:00 UT in heliocentric coordinates. In this study, we mainly focus on MHD waves in the sunspot umbra. Since the observed sunspot is not at the disk center, we divided observed amplitudes by $\cos \theta$, where $\theta$ is a heliolongitudinal angle $\sim 31^\circ$ from the meridional line. Here it is assumed that the observed fluctuations are mainly in the direction of the umbral magnetic field, which is almost normal to the solar surface. This assumption will be reasonable according to the mode identification shown later.

Figure 2 is a snapshot of the sunspot observed in Ca II H, with the positional relationship of the data used in this study. The yellow line gives the slit position for the IRIS raster data, with the red rectangle giving the field of view of the SOT’s spectropolarimeter (SP; Lites et al. 2013) at the observing period. The SP observation was carried out for a region of interest at 15:39–16:31 UT, while the IRIS observation was carried out at 15:48–17:57 UT. We chose an overlapped part of the observation time (15:48–16:31 UT) for our data analysis.
2.1. Hinode SP Observation

The SP recorded the four Stokes ($I$, $Q$, $U$, and $V$) profiles of the Fe I lines at 6301.5 and 6302.5 Å with a spectral sampling of 21.55 mÅ. A 3″8 range was repeatedly mapped with measurements at 12 slit positions, one spectral measurement with a slit width of 0″15 and then the next measurement after moving 0″30 in the west direction (a sparse raster scanning). One measurement with the accumulation of photons in 1.6 s archived the cadence of 27 s in mapping. The two pixels were summed in the slit direction, providing spectral data with a pixel size of 0″32. We used the calibrated Stokes data (Level 1 data) available via CSAC at HAO/NCAR, which is calibrated with the standard SOT–SP calibration software (Lites & Ichimoto 2013).

2.2. Hinode Data Analysis

For the detection of weak magnetic fluctuations, Stokes $V$ is preferable to Stokes $Q$ and $U$ because of its much higher sensitivity. We used the Stokes $I$ and $V$ profiles of the Fe I λ6301.5 line to derive the LOS velocity, the LOS magnetic flux density, and the intensity. The LOS velocity was derived by applying a single Gaussian fit to the Stokes-$I$. Since the magnetic filling factor inside the sunspot umbra is almost unity, effect of the nonmagnetic atmosphere is negligible. The intensities at the line core ($I_{\text{core}}$) and the continuum ($I_{\text{cont}}$) are defined as

$$I_{\text{cont}} \equiv \left\langle \int_{\lambda=6301.0}^{6300.9} I(\lambda) \, d\lambda \right\rangle$$  \hspace{1cm} (1)

and

$$I_{\text{core}} \equiv \min[I(\lambda)]_{\lambda=6302}^{6301}.$$  \hspace{1cm} (2)

Following Fujimura & Tsuneta (2009), the area of Stokes $V$ profiles was used to derive the LOS magnetic flux density (the so-called “weak-field approximation”). The weak-field approximation is valid inside sunspot umbrae according to Felipe et al. (2014) with synthetic profiles of the Fe I λ6301.5 line. We first calculated the degree of the circular polarization CP as defined by

$$\text{CP} = \frac{V}{I_{\text{cont}}}. \hspace{1cm} (3)$$

![Figure 2.](image-url)
where

\[ V \equiv \int_{6301.0}^{6302.0} |V(\lambda)| d\lambda. \] (4)

A coefficient is needed to convert the CP to the LOS magnetic flux density \( B_{\text{LOS}} \). The coefficient was determined by a linear regression line in the scatter plot between the CP and \( B_{\text{LOS}} \) derived from a Milne–Eddington inversion (Figure 3). The linear regression is given by

\[ \text{CP} = (5.8 \times 10^{-5})B_{\text{LOS}} + 0.0027. \] (5)

The data used here are all the SP spectra taken during 15:43–15:56 UT.

It should be noted that the Stokes inversion with the Milne–Eddington inversion, they were noisy. The dominant periods are around 0.17, and the cadence is 3 s. At the same time, the series of slit-jaw images (SJs) for \( \text{Si IV} \) at 1403 K, C II at 1401 K, Mg II at 104.8 K, and the Mg II wing at 103.7 K were obtained every 12 s. Their field of view is 35′′ × 40′′, and they were used to identify the exact location of the slit on the solar features. We used the level 2 data created with the instrumental calibration including the dark current subtraction, flat field, and geometrical corrections (De Pontieu et al. 2014).

2.4. IRIS Data Analysis

We applied a single Gaussian fit to the Mg II k \( \lambda 2796 \) and Si IV \( \lambda 1403 \) spectra independently to derive the LOS velocity at two different temperatures. Here the center position of each spectral line averaged over the field of view was used as the reference wavelength. Since the Mg II spectral line, which has large opacity, is formed in a non-LTE condition, a central reversal is typically observed in the line core (Leenaarts et al. 2013a, 2013b; Pereira et al. 2013). However, note that the Mg II lines observed in sunspot umbrae have no central reversed profiles as reported by Morrill et al. (2001). The intercombination multiplet of O IV lines at 1397.2, 1399.8, 1401.2, 1404.8, and 1407.4 Å provides a well-known set of density-sensitive pairs. We used the ratio of the \( \lambda 1399.8 \) and \( \lambda 1401.2 \) lines for electron density, and we did not use the other lines because of our spectral coverage and line blending (Young 2015).

2.5. Data Co-alignment

The time series of the SP mapping data was aligned spatially by performing the local cross-correlation of the SP continuum image with the subsequent frame. The time series of the SJs at the Mg II wing was also aligned with the same procedure. In both alignments, photospheric sunspot features such as umbrae and penumbrae worked as fiducial marks. Then, the SP maps were co-aligned with the IRIS images by using the SP continuum image and the Mg II wing SJ at the start of each time series. Bright features seen outside the sunspot were used as fiducial marks for the SP–IRIS co-alignment. The aligned field of view is shown in Figures 2(a) and (b). The IDL procedure get-correl-offsets.pro was used to get a rigid displacement in the cross-correlation. Note that SP maps were stretched in the X-direction before the co-alignment because of the sparse raster mapping. In addition, the pixel scale of the SP maps was scaled to that of the IRIS SJs by using the IDL procedure congrid.pro. The accuracy of the co-alignment is better than 0″5 according to the visual inspection of the co-aligned data. The slit position seen in the time series of SJs was checked to confirm the positional fluctuations of the slit on the solar surface with a magnitude of much less than 1″.

3. RESULTS

3.1. Oscillations at the Photosphere Observed with Hinode

Figure 4 shows the temporal evolution of the Doppler velocity, the magnetic flux density, and the line core intensity, derived from the SP data averaged in the 6 × 6 pixel (1″92 × 1″80) area inside the sunspot umbra specified by the purple square in Figure 2(c). Periodic oscillating features are visible in the profiles. The dominant periods are around 5 minutes. Note that we subtracted the 12-point (324 s) running
average from the original time series data to remove the long-term gradual change in the profiles. Since the wave features are similar to sinusoidal functions, we derived the amplitude of the fluctuations by multiplying \( \sqrt{2} \) by the rms values. The results are tabulated in Table 1, where the subscripts \( z \) and 0 mean that these values are perpendicular components to the solar surface and absolute values, respectively. The typical scale factor for DN is about 76 charges in a CCD pixel (Lites et al. 2013).

The uncertainties in \( \Delta v_z, \Delta B_z, \Delta I_{\text{core}}, \) and \( \Delta I_{\text{cont}} \) were estimated to be 2.9 G, 0.0014 km s\(^{-1}\), 0.37 DN s\(^{-1}\), and 0.60 DN s\(^{-1}\), respectively. The uncertainties in \( \Delta B_z \) derived with Stokes \( V \) profiles were obtained by taking account of the standard deviation of intensity fluctuations by photon noise in a continuum range of Stokes \( V \) profiles. The uncertainties in \( \Delta v_z, \Delta I_{\text{core}}, \) and \( \Delta I_{\text{cont}} \) derived with Stokes \( I \) profiles were estimated to be \( \sqrt{\text{photon count}} \) assuming the Poisson distribution.

To determine the phase relations among the Doppler velocity, the magnetic flux density, the core intensity, and the...

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**Table 1**

| \( \Delta B_z \) (G) | \( \Delta v_z \) (km s\(^{-1}\)) | \( \Delta I_{\text{core}} \) (DN s\(^{-1}\)) | \( \Delta I_{\text{cont}} \) (DN s\(^{-1}\)) | \( \Delta B_z/\Delta B_0 \) (%) | \( \Delta I_{\text{core}}/\Delta I_0 \) (%) | \( \Delta I_{\text{cont}}/\Delta I_0 \) (%) |
|---------------------|--------------------------|----------------------|----------------------|--------------------------|--------------------------|--------------------------|
| 20 ± 2.9            | 0.13 ± 0.0014            | 11 ± 0.37            | 12 ± 0.60            | 0.98 ± 0.15              | 0.70 ± 0.015              | 0.78 ± 0.024              |

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Figure 4. From the left to the right, time series of the Doppler velocity, the magnetic flux density, and the intensity in the line core, derived from the SP Fe I \( \lambda 6301.5 \) measurements. The lower panels are their residuals (\( \Delta v_z, \Delta B_z, \Delta I_{\text{core}} \)) after subtracting the 12-point running average from the original time series. Positive and negative velocities imply blueshift and redshift, respectively.

Figure 5. Correlation coefficient for physical parameters observed in the sunspot umbra as a function of time lag. Each symbol implies the pair of physical parameters. Black diamonds, blue asterisks, red triangles, and orange squares show correlation coefficients on \( \Delta I_{\text{cont}}-\Delta B_z, \Delta v_z-\Delta I_{\text{cont}}, \Delta v_z-\Delta B_z, \) and \( \Delta I_{\text{core}}-\Delta I_{\text{cont}} \), respectively. Note that the correlation coefficient was obtained for each time lag by giving the time lag to the time profile of the latter in the two physical parameters.
continuum intensity, we obtained cross-correlation coefficients in the time profile between two quantities from these four parameters. Figure 5 shows the cross-correlation coefficients between two of the observed parameters as a function of the time lag. The cross-correlation coefficient was obtained when a time lag was given to one of the two time profiles. Such calculations were made for 11 different time lags. The correlation coefficient between $\delta I_{\text{core}}$ and $\delta I_{\text{cont}}$ is at maximum with no time lag, meaning that there is no phase shift between $\delta I_{\text{core}}$ and $\delta I_{\text{cont}}$. The correlation coefficient between $\delta I_{\text{core}}$ and $\delta B_z$ is at minimum with no time lag, implying a phase difference between $\delta I_{\text{core}}$ and $\delta B_z$ by $\pi$ radians ($180^\circ$). The correlation coefficient between $\delta v_z$ and $\delta B_z$ is close to zero with no time lag and gradually decreases with increasing time lag, meaning that the $\delta v_z$ time profile is delayed by $\frac{\pi}{2}$ radians ($90^\circ$) from the $\delta B_z$ time profile. Similarly, the $\delta v_z$ is $\frac{\pi}{2}$ radians ($90^\circ$) ahead of $\delta I_{\text{core}}$. Since the phase relations among the magnetic flux density, the Doppler velocity, and the core intensity depend on wave mode (Fujimura & Tsuneta 2009), the phase relations among these values are important for identifying the mode of the observed waves, which will be discussed in Section 4.1.1. The phase relations described above are common at any locations inside the sunspot umbra, as shown in Figure 6, which shows the spatial distribution of the cross-correlation coefficients of the physical parameters at three time lags ($-54$, 0, and $+54$ s). Note that the time lag of 54 s corresponds to $\frac{\pi}{4}$ of the oscillation.

3.2. Oscillations at the Chromosphere and the Lower Transition Region Observed with IRIS

Figure 7 shows the temporal evolution of the Doppler shift measured with the photospheric FeI λ6301.5 line, compared with the corresponding profile of the SiIV lower transition region line. The Doppler velocity of the SiIV line is derived from the spectral profile averaged in 3 pixels along the IRIS slit, which is overlapped with the region of interest given by the purple square in Figure 2. Compared to the FeI profile, the sawtooth pattern is clearly seen in the temporal evolution of the SiIV velocity. The waveforms observed in the SiIV profile have higher frequency than those in the FeI profile. The same nature of the waves can be seen in the Fourier power of the velocities, as shown in Figure 8. We subtracted the 324 s running average from both original profiles before calculating the Fourier transform. Therefore, the orbital effect of the satellite (about 90-minute cycle) is negligible. Figure 9 shows the temporal evolution of Doppler velocities measured with the chromospheric MgII λ k line and SiIV lower transition region line. The oscillation in the SiIV time profile is about 20 s delayed from the oscillation in the MgII k profile. Note that a similar behavior can be found in Tian et al. (2014). The amplitude of the MgII k and SiIV oscillations is 2.0 and 6.2 km s$^{-1}$, respectively. The electron density ($N_e$) was derived by using a pair of emission lines (OIV $\lambda\lambda$1399.8, 1401.2). With CHIANTI v8.1 (Del Zanna et al. 2015), it is $2.6 \times 10^{10}$ cm$^{-3}$.

4. DISCUSSIONS

In this section, we estimate the dissipated energy flux at the chromosphere. For estimating the energy flux, we need to identify the wave mode (Section 4.1). After the mode identifications, we will estimate the energy fluxes at both the photosphere and the lower transition region with the observed amplitudes (Section 4.2). Comparing the energy at the photosphere and the lower transition region, we discuss the dissipated energy of the observed MHD waves and its implications for the heating of the solar atmosphere (Section 4.3).

4.1. Mode Identification of the Waves

For mode identifications, we use the following observed results:

1. The phase relations between two of the intensity $\delta I_{\text{core}}$, the magnetic flux density $\delta B_z$, and the Doppler velocity $\delta v_z$.
2. The dominant frequency of the chromospheric waves is higher than that of the photospheric waves.

3. The wave oscillation in the lower transition region Si IV line is about 20 s delayed from that in the chromospheric Mg II k line.

4.1.1. The Wave Mode at the Photosphere

The appearance of fluctuations in the temporal evolution of the intensity can rule out the incompressible mode, because the intensity fluctuation is proportional to the fluctuation of the electron density even in the optically thick condition. In the MHD theory, there are two compressible wave modes, i.e., fast mode and slow mode. The difference between the fast-mode and slow-mode waves is the phase relation of restoring forces. For the fast-mode waves, the phase relation between the gas pressure and magnetic pressure is in-phase. It becomes the opposite for the slow-mode waves, i.e., the out-phase relation between the gas pressure and magnetic pressure. The gas pressure and magnetic pressure are proportional to the intensity and magnetic flux density, respectively. Thus, for the fast-mode waves, there is no phase difference in temporal evolution between the magnetic flux density and the intensity, whereas the phase difference is $\pi$ radians for the slow-mode waves. Our observations show that the phase difference is close to $\pi$ radians. Thus, we can rule out the fast-mode waves. For slow-mode waves, according to Fujimura & Tsuneta (2009), the observed phase relations, i.e., $-\pi$ radians between the intensity and magnetic flux density, $-\frac{\pi}{2}$ radians between the Doppler velocity and magnetic flux density, and $\frac{\pi}{2}$ radians between the Doppler velocity and intensity, suggest the dominant presence of standing waves. For the above reasons, we suggest that standing slow-mode waves are dominant at the photosphere.

4.1.2. The Wave Mode at the Chromosphere and the Lower Transition Region

Since IRIS cannot perform spectropolarimetric observations, we cannot identify the wave mode by using the phase relations.
of the observed parameters. On the other hand, IRIS observes not only one line but several lines. Considering the different formation heights of the chromospheric Mg II k line and the lower transition region Si IV line, the clear phase difference in these lines shown in Figure 9 implies that the chromospheric waves propagate upward. The observed time lag between MgII and Si IV is around 20 s. The difference of the height in the line formation between Mg II k and Si IV is about 0.5 Mm (Rathore et al. 2015), and thus their propagating speed is roughly 25 km s$^{-1}$, which is close to the sound speed in the atmosphere where Mg II k (T $\sim$ 10,000 K and $c_s \sim$ 15 km s$^{-1}$) and Si IV (T $\sim$ 80,000 K and $c_s \sim$ 40 km s$^{-1}$) are formed. A steepening is observed with IRIS as a possible sign of shock formation and energy dissipation. Since longitudinal waves are easily steepened compared to transverse waves, the observed steepening signature also supports the identified slow-mode waves at the photosphere. The dominant frequency of the chromospheric waves is $\sim$7 mHz, whereas the observed dominant frequency is $\sim$3.7 mHz at the photosphere. The similar high-frequency enhancements were reported by Centeno et al. (2006, 2009) in the sunspot umbra. The change of the dominant power to higher frequency can be explained with the acoustic cutoff. The oscillations below the cutoff frequency do not propagate upward. On the other hand, above the cutoff value, waves propagate upward freely into the chromosphere. Photospheric standing mode is a consequence of cut and reflected waves, because the frequencies of almost all the photospheric waves are below the cutoff frequency, which is roughly $\sim$6 mHz, i.e., the lower edge of the strong IRIS power (Figure 8).

4.2. Energy Estimation

In this section, we estimate the energy flux based on the identified wave mode (dominant photospheric standing slow-mode waves with leakages of the high-frequency wave components to the chromosphere) and the observed amplitudes.

The energy flux $F$ is generally written by

$F = \rho \omega^2 v_r + (\omega \times B) \times \mathcal{J}B$,  \hspace{1cm} (6)

where $\rho$, $B$, $v$, and $v_r$ are the mass density, the magnetic field strength, the velocity amplitude, and the group velocity, respectively. The first and second terms on the right-hand side are thermal–kinetic energy flux and Poynting flux, respectively. The energy flux of the slow-mode wave is described as

$F = \rho \omega^2 v_r$.  \hspace{1cm} (7)

Note that since the direction of $\omega$ is the same as $B$ in the case of slow-mode waves, the Poynting flux term,

$(\omega \times B) \times \mathcal{J}B$,  \hspace{1cm} (8)

is zero.

4.2.1. Energy Flux at the Photosphere

For estimating the energy flux, we need to estimate the mass density at the photospheric height. Assuming a uniform straight cylinder as a flux-tube model, Moreels & Van Doorsselaere (2013) analytically calculated that the photospheric phase speed for the slow-mode waves can be written by

$$ \frac{\omega}{k} = c_s \sqrt{\frac{\partial A_{\text{cont}}/\partial T}{\partial B_z/B_0} \left[ \frac{2 \hbar v}{3 k_B T} + \frac{\partial A_{\text{cont}}/\partial T}{\partial B_z/B_0} \right]^{-1/2}}. \hspace{1cm} (9)$$

The phase speed of slow-mode waves is close to $c_T$ (Edwin & Roberts 1982), where the tube speed $c_T = \sqrt{\frac{\gamma \rho}{\gamma + \rho}}$, the sound speed $c_s = \sqrt{\frac{\gamma k_B T}{m}}$, and the Alfvén speed $v_A = B_0 / \sqrt{4\pi \rho}$. Therefore, the comparison between Equation (9) and $c_T$ gives $\rho = 5.0 \times 10^{-6}$ g cm$^{-3}$ by substituting the observed parameters (Table 1) and $T = 4500$ K. Figure 8 suggests that the waves with a frequency above 6 mHz can penetrate into the chromosphere. Thus, the upward energy flux at the photosphere ($F_{\text{Hinode}}$) is estimated by using the Doppler velocity amplitude $\Delta v_r = 0.027$ km s$^{-1}$, which is derived from the 6–10 mHz data and is sufficiently larger than the noise level estimated by photon noise (0.0014 km s$^{-1}$). Note that the strong IRIS power exists in the 6–10 mHz range. The waves in the 6–10 mHz may propagate to the chromosphere because of a frequency higher than the cutoff frequency. With $\rho = 5.0 \times 10^{-6}$ g cm$^{-3}$ and $|v_r| = c_s = 5.4$ km s$^{-1}$, we derive $F_{\text{Hinode}} = 2.0 \times 10^7$ erg cm$^{-2}$ s$^{-1}$.

4.2.2. Energy Flux at the Lower Transition Region

The energy flux of the waves at the formation height of the Si IV line is estimated with the observed amplitude of the Doppler velocity, i.e., $\Delta v_r = 6.2$ km s$^{-1}$. Here we use the sound speed of 40 km s$^{-1}$, calculated with the formation temperature of Si IV and the mass density $\rho$ of $5.4 \times 10^{-14}$ g cm$^{-3}$. The mass density is given by $\rho = N_e \mu m_p$, where $m_p$ is the proton mass ($m_p = 1.67 \times 10^{-24}$ g) and $\mu = 1.25$ from the solar atomic abundance H:He = 3:1. The electron density ($N_e$) used here is $2.6 \times 10^{10}$ cm$^{-3}$, which was derived from a pair of emission lines (O IV $\lambda 1399.8$, 1401.2). Note that the plasma observed with the O IV lines is almost the same as that with Si IV, as reported by Martínez-Sykora et al. (2016). With these parameters, we obtained an energy flux of $8.3 \times 10^4$ erg cm$^{-2}$ s$^{-1}$. The corona above sunspot umbrae is sometimes dark in soft X-rays. However, Nindos et al. (2000) reported that sunspot temperatures and emission measures at the corona are still lower than the average active region parameters but higher than the quiet-region plasma parameters. Since the coronal energy loss at the quiet region is about $3 \times 10^5$ erg cm$^{-2}$ s$^{-1}$ (Withbroe & Noyes 1977), which is larger than our estimated energy flux at the lower transition region, we can say that our estimated energy flux is not enough for the requirement of the coronal heating. Furthermore, we should note that the estimated density might be overestimated by up to several factors, because of the nonequilibrium ionization effect (Olluri et al. 2013; Young 2015). Since the density is proportional to the energy flux, the energy flux might also be overestimated by up to several factors.

4.3. Implications for the Heating of the Solar Atmosphere

The energy fluxes estimated in this study are summarized in Figure 10. The difference of the energy flux between $F_{\text{Hinode}}$ and $F_{\text{IRIS}}$ may be considered as the amount of energy dissipated by the waves before they reach the transition region level. The dissipated energy flux is enough to heat the umbral
chromosphere (about $2 \times 10^8$ erg cm$^{-2}$ s$^{-1}$ from Avrett 1981; Lee & Yun 1985). This means that the dissipation of the compressible shock waves is crucial to form the umbral chromosphere. Since the magnetic field in sunspot umbrae is highly bundled, we guess that the discontinuity of the magnetic field is not likely to be created inside umbral fields. Therefore, small energy releases such as nanoflares might not contribute to the atmospheric heating in sunspot umbrae. The energy flux observed with the Si IV line is much smaller than the energy input required for the coronal heating in umbrae. This suggests that other heating mechanisms may be important in the corona, at least in the coronal magnetic structures connecting to sunspot umbrae.

We should note that our estimated photospheric density is larger than that in standard empirical atmospheric models, such as Maltby et al. (1986) and Fontenla et al. (2006). As an example, in the Maltby et al. (1986) model, the mass density $\rho$ is less than $10^{-7}$ g cm$^{-3}$ at $z = 300$ km, which corresponds to the formation height of the Fe I $\lambda$6301.5 line (Felipe et al. 2014). If we assume the photospheric density of the Maltby et al. (1986) model, the dissipated energy flux becomes smaller than the requirement for the chromospheric heating. Therefore, it is quite important to understand the reasons for the discrepancy. We have three ideas.

The opacity effect may be one of the reasons why the photospheric density estimated with the seismology has a relatively large value, as discussed in Lites et al. (1998), Bellot Rubio et al. (2000), Khomeiko et al. (2003), and Felipe et al. (2014). Temperature and density fluctuations associated with the propagation of compressible waves may cause fluctuations in opacity; the line formation layer is moved upward and downward, resulting in an apparent fluctuation in magnetic flux density. For estimating the photospheric density, we assume here that the observed fluctuations of magnetic flux density are fully intrinsic ($\delta B = \delta B_{\text{intrinsic}}$). However, there is a possibility that the opacity effect may cause a false signal in the fluctuations in the magnetic flux density ($\delta B = \delta B_{\text{intrinsic}} + \delta B_{\text{opacity}}$). There is no phase difference between the density increase and the rising motion of the line formation height. Thus, when we only consider the opacity effect caused by density fluctuation, the phase difference between $\delta \rho_{\text{core}}$ and $\delta B$ is observed as out of phase ($\pi$ radians), which is the same as what we observed. This means that the observed $\delta B$ gives the maximum value of $\delta B_{\text{intrinsic}}$. Figure 11 shows the photospheric mass density derived by the seismology as a function of $\delta B_{\text{intrinsic}}$. This shows that the density becomes small when $\delta B_{\text{intrinsic}}$ becomes small. By performing a numerical simulation, Rüedi & Cally (2003) suggested that most of the expected fluctuations in the magnetic flux density are actually due to a cross-talk from the temperature and density oscillations associated with MHD waves, implying the opacity effect. However, Felipe et al. (2014) simulated a synthetic observation with the Fe I $\lambda$6301.5 line and suggested that the photospheric magnetic field retrieved from the weak-field approximation provides the intrinsic oscillations in magnetic flux density associated with the wave propagation because of the low magnetic field gradient. This implies the importance of the vertical magnetic field structure. Collados et al. (1994) reported that the difference in vertical gradient of the magnetic flux density observed in the large sunspot’s umbrae is about $-0.25$ G km$^{-1}$. Since this value is close to the condition used in Felipe et al. (2014), there is a strong possibility that observed magnetic fluctuations are intrinsic.

The second possible reason is because of the simplified modeling for the seismology. Since the straight cylinder model (Moreels & Van Doorsselaere 2013) does not consider the expanding magnetic shape and the density stratification, there are some differences between the modeling and the observed sunspot.

The third possible reason is due to the temperature reduced in the sunspot umbra. The temperature reduced at the umbral photosphere may reduce the amount of $H^-$ ion, which is a dominant absorber in the visible wavelength (e.g., Stix 2002). As a consequence, the line formation layer moves downward and may increase our density estimate to a higher value because of the gravity stratification. Previous studies, such as Mathew et al. (2004) and Martinez Pillet & Vazquez (1993), obtained that the magnitude of the Wilson depression is 400–800 km in the umbra, which is sufficiently longer than the scale height at the photosphere ($\sim 150$ km).

At the end, we should note possibilities that a fraction of the derived difference of the energy flux at the two atmospheric layers may not be the dissipated energy. For example, if ascending photospheric waves refract and do not reach the chromosphere, there is an energy difference, but the energy is not dissipated in the chromosphere. In this study, since slow-mode waves are generally thought to propagate along the magnetic field, the effect of refraction might not be important in sunspot umbrae, where magnetic fields are almost perpendicular to the solar surface. Tracing waves from the photosphere to the chromosphere also helps us understand their true connection. Löhner-Böttcher & Bello González (2015) found photospheric oscillations in sunspot penumbras that have a slightly delayed counterpart of more defined chromospheric running penumbral waves with larger relative velocities, suggesting that the running penumbral waves propagate upward along inclined magnetic field lines. Inside sunspot
umbrae, since waveforms in the photosphere and the chromosphere are not similar to each other because of acoustic cutoff and nonlinear interaction, it is not easy to trace waves like Löhner-Böttcher & Bello González (2015). For considering acoustic cutoff, Fourier filtering is sometimes applied for investigating the propagating processes (Centeno et al. 2006, 2009; Felipe et al. 2010). Fourier analyses cannot be applied to nonlinear characteristics (especially seen in the chromosphere), and thus we need to develop such a method in the future for tracing waves from the photosphere to the chromosphere more strictly.

5. SUMMARY AND CONCLUSIONS

Using a unique data set from the observations coordinated between Hinode and IRIS, we investigated the nature of fluctuations in the temporal evolution of physical parameters observed in the sunspot umbra. After identifying the wave mode of the observed fluctuations, we estimated upward energy fluxes at both the photospheric and transition region layers with the Hinode and IRIS satellites. The difference in these energy fluxes is considered as the dissipated energy in the region between the two atmospheric layers.

We detected periodic fluctuations in the temporal evolution of the photospheric FeI, chromospheric MgII k, and lower transition region SiIV lines. We concluded that there are fluctuations in the temporal evolution of the magnetic flux density. Therefore, what we need to do next is to distinguish $\Delta B_{\text{intrinsic}}$ and $\Delta B_{\text{opacity}}$ for a better quantitative estimate of the energy flux. Hinode is a Japanese mission developed and launched by ISAS/JAXA, with NAOJ as domestic partner and NASA and STFC (UK) as international partners. It is operated by these agencies in co-operation with ESA and NSC (Norway). IRIS is a NASA small explorer mission developed and operated by LMSAL with mission operations and executed at NASA Ames Research center and major contributions to downlink communications funded by ESA and the Norwegian Space Centre. We sincerely thank the Hinode team and the IRIS team for providing the coordinated observations used in this article. The authors are supported by MEXT/JSPS KAKENHI Grant Numbers 25220703 (R.K.), 25220703, 15H05750, 15H05814 (T.S.), 25220703, 26287143, and 15H05816 (S.I.).

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