A New Approach to Kinetic Energy Flux at the Different Frequencies above the IRIS Bright Points*

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Abstract

Various bright structures abound in the chromosphere playing an essential role in the dynamics and evolution therein. Tentatively identifying the wave characteristics in the outer solar atmosphere helps to understand this layer better. One of the most significant aspects of these characteristics is the wave phase speed (PS), which is a dominant contribution to solar coronal heating and energy distribution in the Sun’s atmosphere layers. To obtain energy flux (EF), it is necessary to calculate the filling factor (FF) and the PS. In this study, the FF was determined by tracking the size and intensity of the IRIS bright points (BPs). To estimate an accurate PS and EF, it is necessary to know the chromosphere and transition region (TR) thickness and the phase difference between the two desired levels. Chromosphere and TR thickness cannot be measured directly on the disk; this study is performed using spectral data and calibrated based on Doppler velocities. As a result, the PSs in active regions (ARs) and coronal holes (CHs), as well as the IRIS BPs, have been calculated using the cross-power wavelet transform of Doppler velocities. Consequently, about the CH, the PS mean values are from 40 to 180 km s\(^{-1}\) at the network and from 30 to 140 km s\(^{-1}\) at the internetwork; and about the AR, they are from 80 to 540 km s\(^{-1}\) at the network and 70 to 220 km s\(^{-1}\) at the internetwork. Finally, the EF for the IRIS BPs has been calculated in three different frequencies. The results indicate that the network BPs have an influential role in heating the higher layers, while in the internetwork BPs most of the energy returns to the lower layers.

Unified Astronomy Thesaurus concepts: The Sun (1693); Quiet solar chromosphere (1986); Solar corona (1483); Solar transition region (1532)

1. Introduction

Bright points (BPs) and activities that abound in active regions (ARs), including explosive events, coronal holes (CHs), and quiet Sun (QS) network and internetwork brightness, have indicated strong signatures of the magnetic field, and thanks to the unprecedented spatial and spectral resolution of Interface Region Imaging Spectrometer (IRIS; De Pontieu et al. 2014), activities have been seen on even finer scales. Chromosphere and transition region (TR) thickness are very dynamic (e.g., Tavabi et al. 2015b, 2011), and this dynamism makes it difficult to measure the characteristics of these layers (e.g., Leenaarts et al. 2010; Vilinga & Koutchmy 2005). The height of the solar chromosphere is seen in the visible and radio wavelengths. There are problems in measuring this height. For example, solar spicules have different heights. Also, solar flares, usually higher than the chromospheric surface, have variable heights (Aschwanden et al. 2002; Tavabi & Koutchmy 2019; Tavabi et al. 2011). It is difficult to distinguish between the height of the chromosphere and the TR layer. Measuring the height of the solar atmosphere in the lower layer is more dependent on hydrostatics and energy balance, in contrast, in the upper layers, height values are highly dependent on dynamic factors (Fontenla et al. 2002). In near-solar limb data, photospheric data have the lowest participation rate compared to other spatial locations. As a result, it allows the chromosphere to be examined without disturbing the photosphere data. Some huge values such as 28 Mm show the altitudes at the maximum length of macrospicules; this height more or less refers to the inner corona levels, which is dominated by chromospheric plasma or macrospicules (Kiss et al. 2017). Using IRIS spectral data, Alissandrakis et al. (2018) obtained the altitudes above the visible limb at Mg k and h peaks 6.909 and 6.539 Mm, respectively. The Mg II spectrum has two distinct peaks, k and h (Figure 1), and also smaller peaks in the range between the two apparent peaks (such as single peaks of Fe I, Ni I, Mn I, and Cr II) and so, the most characteristic of them, triple Mg II lines and Fe II lines (Leenaarts et al. 2013; Pereira et al. 2015).

These triple lines have wavelengths of 279.160, 279.875, and 279.882 nm. The triple lines are formed due to a sharp rise in temperature of more than 1500 k in the lower chromosphere; the Fe II peak has a wavelength of about 280 nm (Leenaarts et al. 2013; Pereira et al. 2015).

In addition, Tian et al. (2014) found subarcsecond bright dots (BDs) implicating heating events in the TR on ARs above the umbrae and penumbras of sunspots. Deng et al. (2016) reported that these BDs are unrelated to the chromosphere and suggested their TR formation. Kleint et al. presented IRIS evidence of small-scale brightness, which are low corona small loops that emit in UV (Madjarska 2019; Berghmans et al. 2021; Li 2022) – associated with supersonic downflows, which have enough energy to heat the TR above sunspots. However, penumbral jets have been considered with IRIS observations and were suggested to be heated to TR temperature (Vissers et al. 2015).

In the past, solar physics researchers have used chromosphere and TR thickness values using ground-based and space
observational data and with different element lines (e.g., Auchere et al. 1998; Filippov & Koutchmy 2000; Georgakilas et al. 1999; Johannesson & Zirin 1996). Alissandrakis et al. (2018) in their research on spicules and structures near the solar limb reported that the value of height limb (in the area where there are no CHs) for the Mg II k peak is about 9.5 Mm; this value for Mg II h is slightly less than 9 Mm and about 2.5 Mm for the Mg II triplet 1 peak (279.160 nm), slightly less than 3 Mm for Mg II triplet 2 peaks (279.875 nm), and about 1.5 Mm for Mg II triplet 3 peaks (279.882 nm), and this amount is slightly less than 1.5 Mm for the Fe II peak (280.009 nm). IRIS data allow us to obtain the chromosphere and TR thickness values at high spatial resolution (De Pontieu et al. 2014) and calibrate its values in terms of wavelength, and consequently Doppler velocity. Mein & Mein (1976) have stated that the chromosphere height based on phase can be derived where its phase is equivalent to the Doppler phase shift. Therefore, the phase difference can be obtained based on the height difference. Mein & Mein (1976) calculated the phase speed to be less than 10 km s$^{-1}$. Morton et al. (2012) has calculated the phase speed of about 48 to 325 km s$^{-1}$ for different regions of the QS. Abramov-Maximov et al. (2011) have also stated in their research that the phase speed is 30 to 50 km s$^{-1}$.

Another factor that affects chromospheric height and phase speed is the nature of study areas (Sturrock 1964; Solanki & Steiner 1990; Athay 2012; Solanki 2004; Carlsson et al. 2019).

Recently, solar research groups have studied the energy flux of the Sun’s surface in the chromosphere and corona (e.g., Li et al. 2022; Morton et al. 2012; Petrova et al. 2022; Zeighami et al. 2016). Morton et al. (2012) estimated that the total flux of energy on the surface of the Sun that can reach from the chromosphere to the corona is about 170 ± 110 W.m$^{-2}$ for incompressible transverse motions and 460 ± 150 W.m$^{-2}$ for compressional motions. Petrova et al. (2022) have calculated the energy flux of the coronal high-frequency oscillations to be 1.9 ± 0.68 kW.m$^{-2}$ for 14 s oscillations and 6.5 ± 1.4 kW.m$^{-2}$ for 30 s oscillations.

IRIS obtained spectra in near-ultraviolet (NUV), far-ultraviolet 1 (FUV1), and far-ultraviolet 2 (FUV2), from 1332 to 2834 Å. Slit jaw images (SJIs) of IRIS by using various filters can provide images centered on the Mg II wing, Mg II k, Si IV 1403 Å, and C II line (De Pontieu et al. 2014, and see the IRIS Technical Note 20 for details).

It should be noted that Mg II lines are usually for plasma with low temperatures and above the minimum temperature $T_{500} = 1$ because it is an element with the low first ionization potential (FIP). The achieved velocity resolution for IRIS spectra is 0.5 km s$^{-1}$.

The observational data used for determine chromosphere and TR thickness were four IRIS sit-and-stare data sequences of different areas of the Sun; these data include spectra of QS and ARs of the Sun and CH areas and the limb filament loop (LL). The first set of data relates to the north pole and CHs. The second category is loop limb filament data. The third category is data on the QS in the south pole. The fourth category is the data on the active area of the Sun. A brief overview of the IRIS data (level 2) used in this article is given in Table 1. The location of the selected data in this section is visible on the left side of the panels (a), (b), (c), and (d) of Figure 2, and are indicated by green rectangles. In the three IRIS data of AR, QS, and CH, the slit is perpendicular to the Sun’s surface, but not in the limb filament loop; moreover, this difference distinguishes this sample from the other three data. However, there is another great point about this data, which is the existence of a loop in QS areas.

The data used for phase speed measurements are the IRIS sit-and-stare data possesses and spectrum for the two active and CHs in the center of the solar disk.

A brief overview of the IRIS data (level 2) used in phase speed and energy flux measurements is summarized in Table 2.

3. Methods and Data Reduction

Methods and data reduction in this article consists of four parts: chromosphere height, phase speed measurement, filling factor, and energy flux.

First, the IRIS data related to the Mg II spectrum related to specific wavelengths with a width of 0.0025 nm (average data taken from the width of 0.0076 nm) are separated and stacked together based on time, and the intensity time slice

2. Observations

The data used in this study are divided into two categories: data used to determine chromosphere and TR thickness, and data used to measure phase velocity.

![Figure 1.](image)
corresponding to the specific wavelength is created. Once the intensity time slice is obtained, this data is averaged over time and converted into a column with a width of 0.0025 nm (Figure 5). The chromosphere and TR thickness corresponding to the specified wavelength is then read from the data column. This process is performed during the frequency range of the

Table 1

| Time [UT]                  | Coronal Hole | Limb Filament Loop | Active Region | Quiet Sun       |
|----------------------------|--------------|--------------------|---------------|-----------------|
| 2017-08-15                 |              |                    |               |                 |
| 23:10:06 to 00:49:31+1d    |              |                    |               |                 |
| X, Y                       | −5°,957°     | 828°, −466°        | 997°,62°      | 6°,−981°        |
| Max FOV                    | 119° x 119°  | 167° x 175°        | 119° x 119°   | 119° x 119°     |
| Roll                       | 0 deg        | −45 deg            | 90 deg        | 0 deg           |
| Raster FOV                 | 0° x 119°    | 0° x 175°          | 0° x 119°     | 0° x 119°       |
| Raster steps               | 1667×0°      | 884×0°             | 380×0°        | 440×0°          |
| Raster step Cad            | 3.6 s        | 15.9 s             | 9.5 s         | 9.8 s           |
| Raster Cad                 | 4 s, 1 ras   | 16 s, 1 ras        | 9 s, 1 ras    | 10 s, 1 ras     |
| SJI FOV                    | 119° x 119°  | 167° x 175°        | 119° x 119°   | 119° x 119°     |
| SJI Cad                    | 1330:4 s, 1666 imgs | Si IV (1400):32 s, 441 imgs | 1330:19 s, 189 imgs | 1330:20 s, 220 imgs |
| OBSID                      | 3624255503   | 3800111404         | 3820259253    | 3800009253      |

Note. Specifications of four series of data used to measure chromosphere thickness, which are sit-and-stare data from IRIS. These data are from CH, LL, AR, and QS regions.
research, which is finally obtained by plotting the chromosphere and TR thickness in terms of the wavelength (right side of (a), (b), (c), and (d) panels of Figure 2 for QS, AR, CH, and LL, respectively). In the diagrams, five prominent regions are seen, which includes two peaks of the Mg II triplet and two peaks of the Mg II k and h spectrum and the Fe II line core. For Doppler velocity calculations, we need to select a reference as zero velocity. Here, the center of the k peak is chosen as zero velocity, and as we move to the right or the red wing, the velocities increase in a positive direction; as we move to the left or the blue wing, the velocity values become more negative. Therefore, the zero velocity referred to the wavelength of 279.639 nm.

To calculate the phase difference of Doppler velocity oscillation, first it is necessary to calculate the Doppler velocity. These calculations are performed using Equation (2). Doppler velocity calculations are performed on the Mg II spectrum for two sets of network and internetwork points in the active and the CH areas. They are calculated for 40 km s$^{-1}$ Doppler velocity (Table 8). For this selection, the maximum Doppler shift graph for Doppler velocity is plotted for Mg II h and k peaks (Figure 3). To perform phase speed analyses, five BPs in the active area and four BPs in the CH area were selected. These points are selected using SJI, and according to what Sadeghi & Tavabi (2022) and Tavabi & Sadeghi (2022) have stated, based on BPs oscillations period, it is determined which group of network and internetwork they belong to. For this purpose, the time series of the Mg II spectrum in the desired range is analyzed by the Morlet wavelet (Torrence & Compo 1998) and the period of oscillations of the BPs is obtained; as a result, network and internetwork points are determined. These BPs are shown in Figure 4 on the SJIs 1401.

Figure 3. The maximum Doppler velocity diagram shows well the red and blueshifts of the spectrum based on the Doppler velocity. Upper left: The maximum Doppler velocity diagram of AR Mg II k. Upper right: the maximum Doppler velocity diagram of AR Mg II h. Bottom left: the maximum Doppler velocity diagram of CH Mg II k. Bottom right: the maximum Doppler velocity diagram of CH Mg II h.

Doppler velocity spectra are then given in pairs as input to the cross-correlation wavelet transform function (Grinsted et al. 2004). This function identifies areas with a high common in the frequency and time period, and the phase difference of the input oscillations can be obtained with optimal time and frequency accuracy.\(^2\)

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1. The wavelet analysis code that was used can be freely downloaded under http://paos.colorado.edu/research/wavelets/.

2. The cross wavelet analysis code that was used can be freely downloaded under http://grinsted.github.io/wavelet-coherence/.

### Table 2

|                | Coronal Hole       | Active Region       |
|----------------|--------------------|---------------------|
| Time [UT]      | 2016-10-14 20:23:19 to 21:45:03 | 2016-08-02 17:59:15 to 19:58:45 |
| X, Y           | 24°, -68"          | -63°, 88"           |
| Max FOV        | 119° x 119°        | 120° x 119°         |
| Roll           | 0 deg              | 0 deg               |
| Raster FOV     | 0° x 119°          | 0° x 119°           |
| Raster steps   | 512x0°             | 1383x0°             |
| Raster step Cad| 9.6 s              | 5.2 s               |
| Raster Cad     | 10 s, 1 ras        | 5 s, 1 ras          |
| SJI FOV        | 119° x 119°        | 120° x 119°         |
| SJI Cad        | Si IV (1400): 10 s, 511 imgs | 16 s, 460 imgs |
|                | Mg II h/k (2796) : 16 s, 461 imgs |
|                | Mg II w s (2832) : 16 s, 461 imgs |
| OBSID          | 3620259603         | 3620106803          |

**Note.** Specifications of two series of data used for phase speed and energy flux analyzes, which are sit-and-stare data from IRIS. This data is from CH and AR regions.
To do this, the nonthermal Doppler velocity time slice must first be obtained for the peaks under study (here $k_3$ and $h_3$). Equation (2) then gives the Doppler velocity for the desired speed (here $\sim 40 \text{ km s}^{-1}$) with a tolerance of $\pm 10.75 \text{ km s}^{-1}$, and slides with a time width of 5.2 s for the active area and 9.6 s for the CH region, which are put together to create a Doppler velocity time slice. These Doppler velocity time slices are given as cross-violet inputs, and in this way, the phase difference in the desired oscillation periods can be obtained, and thus the phase speed can be calculated with the help of chromosphere and TR thickness. Cross-correlation wavelet transform diagrams are shown in Figures 7, 8, 9, 10, and 11 for the AR, and Figures 12, 13, 14, and 15 for the CH.

The filling factor is one of the factors that can be used to calculate energy flux in different areas. The amount of this component varies depending on the activity of the study area. The filling factor is defined as the ratio of the area of BPs to the total area of the study area (Van Doorsselaere et al. 2014). To obtain this factor, we first divided the BPs into two categories, network and internetwork, according to the dimensions and intensity of BPs; this process was performed on 1400 Å images of IRIS and Solar Dynamics Observatory (SDO)/Helioseismic

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**Figure 4.** (a) The positions of points P1 to P5 are shown on SJI 1403 Å (Si IV). This SJI is related to the AR, which was captured on 2016 August 2. In this figure, the intensity is inverted and negatived. (b) The positions of points P6 to P9 are shown on SJI 1403 Å (Si IV). This SJI is related to the coronal hole area, which was captured on 2016 October 14. In this figure, the intensity is inverted and negatived.

**Figure 5.** Upper: Mg II spectral data for a specific wavelength in terms of time. Bottom left: compressed spectral Mg II related to certain wavelength over time. Bottom middle: averaging spectral data over time and converting it to a column. Bottom right: intensity–height graphs for accurate readings of specified chromosphere height at each wavelength.
and Magnetic Imager (HMI) magnetograms at the same time. In Figure 6, the BPs of the network and the internetwork are tracked according to the dimensions and intensity on the SJI Si IV (1400 Å), and the BPs of the internetwork are marked with red triangles and black circles (Figure 6). Also, with the same method, in Figure 6, the internetwork and network BPs on the SDO/HMI magnetogram are marked with red triangles and black circles, respectively (Figure 6). With the help of the specified points and calculating the level of these points and calculating the ratio of the level of these points to the total level, the filling factor can be obtained. The values of obtained for the filling factor in the CH area are given in Table 3.

The energy flux depends on the phase velocity, Doppler velocity, density of BPs, and filling factor, and the formula from this table showing the filling factor for the CH area are in Table 3.

| Period Time (s) | 64 | 180 | 300 |
|----------------|----|-----|-----|
| Network (%)    | 12 | 2   | 5   |
| Internetwork (%)| 12 | 9   | 0   |

Note. This table shows the filling factor for the coronal hole area and for periods 64, 180, and 300 s.

Table 3

Filling Factor of CH

energy flux in different regions of the solar surface (Bate et al. 2022; Van Doorsselaere et al. 2014): 

\[ F \approx \frac{1}{2} \rho v^2 v_{pb}. \]

In this way, the energy flux are obtained using the Doppler velocity and the phase speed and filling factor obtained.

4. Discussion and Conclusion

In the present work, we report that chromosphere and TR thickness in the Mg II spectral lines is investigated and its calibration is performed based on the Doppler velocity in different regions of the Sun, including the poles and the equator, and near the equator, and then the phase speed is determined in each region (corona hole and active area) and on the two types of chromospheric BPs (network and internetwork).

Determining the energy flux and the contribution of each phenomenon from the energy flux transferred to the higher parts of the solar atmosphere, or returned to the lower levels, is one of the most exciting discussions for solar physics researchers and helps to better understand the solar atmosphere and solar heating mechanism.

For this purpose, it is necessary to calculate the filling factor, which is calculated in Section 3. The filling factor is, in fact, the ratio of the cross section of BPs to the total area (Van Doorsselaere et al. 2014). This amount has been calculated by Van Doorsselaere et al. (2014) to be less than 20%. Makita (2003) has also reported a value of 5% by the Ca h and k line. Klimchuk (2012) has reported the value of less than 4.5% for
the filling factor at QS. Tavabi (2018) has stated that coronal bright points (CBPs) and BPs are highly interdependent. Hence, their energy is also highly interdependent. Pres & Phillips (1999) has considered CBPs total radiative to be about $5.6 \times 10^{27}$ to $1.1 \times 10^{28}$ erg and the conductive energy of CBPs to be about $4.0 \times 10^{28}$ to $2.4 \times 10^{29}$ erg. Also, Priest et al. (2003) have stated that the amount of energy is $\sim 10^{18}$ to $10^{20}$ erg s$^{-1}$.

4.1. Line Formation Height above the Limb

In the chromosphere thickness diagram in terms of frequency in the wavelength range of Mg II, four dominant peaks can be distinguished:

1. The first peak of the Mg II triplet peaks is seen around of 279.159 nm.
2. The peak of the Mg II k line, which is the most apparent peak in this spectral range and is seen around the wavelength of 279.632 nm.
3. The peak of Fe II, which is at 280.009 nm, is another peak seen in the Mg II spectral line.
4. The other Mg II triplet peaks in the chromosphere and TR thickness diagram are combined and represented as a peak. These two peaks have wavelengths of 279.875 and 279.882 nm. However, they can be seen in the chromosphere and TR thickness diagram around a wavelength of about 279.879 nm.

5. The peak of the Mg II h, which is one of the most apparent peaks in this spectral range and is seen around the wavelength of 280.358 nm.

Chromosphere and TR thickness values are calculated for four regions and selected times from the Sun, and the five index peaks mentioned (Table 4).

The height difference between the h and k peaks in each of the four study areas is shown in Table 5. Also, the difference between the triplet peaks is expressed in this table.

By comparing the chromosphere thickness values in the QS and the AR, it can be concluded that the chromosphere and TR thickness of the active Sun is 5 times larger than that of the QS (this amount is so significant). This means that knowledge of the area under study is essential to determine the chromosphere and TR height.

Also, as can be seen from the height diagrams in terms of wavelength, the height values change significantly with wavelength changes.

These heights in terms of wavelength can be directly related to changes in chromosphere thickness in terms of changes in all physical parameters associated with wavelength.

Some studies have shown that a number of spicules can transfer a lot of mass and energy to the corona (e.g., Tavabi et al. 2015a). In ARs, magnetic structures higher than other regions are observed. In polar regions, accumulation of CH jets is seen due to open magnetic fields. The altitudes are above the $10 \text{ Mm}$ beyond the inner corona; however, in huge prominence and in ARs with TR miniloops and arcs or monofilaments, the chromospheric rather cool material emission lines are penetrated and seen in higher altitudes; even the low-FIP photospheric element could reach the inner corona and freely contribute to the fast solar wind. Values marked with the asterisk in the Table 4 are more related to the extended chromosphere to the inner corona and are caused by TR penetrated materials (Bennett & Erdélyi 2015; Sow Mondal et al. 2022; Martínez-Sykora et al. 2018).

One of the most important of these indicators is the Doppler velocity, which is directly related to wavelength and is calculated as follows.

$$\Delta \nu_{\text{Doppler}} = \frac{-1}{2} \frac{c}{\lambda_k} \left[ (\lambda_{k_2} - \lambda_k) + (\lambda_{k_3} - \lambda_k) \right],$$

(2)

where $c$, $\lambda_{k_1}$, $\lambda_{k_2}$, $\lambda_{k_3}$ are respectively, speed of light, $k_1$ line center wavelength, $k_2$ observed $k_1$-peak wavelength, $k_3$ observed $k_1$-peak wavelength.

As a result, by considering a reference point for the Doppler velocity, each wavelength can be assigned a number commensurate with the Doppler velocity, and the chromosphere thickness diagram can be plotted against the Doppler velocity.

4.2. Phase Speed Measurement

Zeighami et al. (2020) studied the Doppler velocity above chromospheric network and internetwork points and obtained values of $-21$ to $+21$ for internetwork points and $-20$ to $30 \text{ km s}^{-1}$ for network points. Zhang et al. (2021) reported the Doppler velocity value of a flare-related coronal jet to be about $-120$ to $170 \text{ km s}^{-1}$.

We have recorded the maximum Doppler velocity observed for the AR and CH Mg II h and k as shown in Table 8 (as shown in Figure 3). The maximum Doppler shift velocity at the network BPs is $49 \text{ km s}^{-1}$ for the blueshift and $+50 \text{ km s}^{-1}$ for

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**Table 4**

| Name          | Wavelength (nm) | CH (Mm) | LL (Mm) | AR (Mm) | QS (Mm) |
|---------------|-----------------|---------|---------|---------|---------|
| Mg II triplet | 279.159         | 0.7     | 0.8     | 0.5     | 1.1     |
| Mg II k       | 279.632         | 15.3    | 4.5     | 39.2*   | 8.8     |
| Mg II triplet 2| 279.879        | 1.8     | 0.9     | 0.9     | 1.4     |
| Fe II         | 280.009         | 0.8     | 0.6     | 0.6     | 0.7     |
| Mg II h       | 280.358         | 14.6    | 4.2     | 38.3*   | 7.8     |

**Note.** This table shows the chromosphere and TR thickness of the four regions under discussion (CH, LL, AR, QS). Values marked with an asterisk in the table are more related to the extended chromosphere to the inner corona and are caused by TR penetrated materials.

**Table 5**

| Name          | CH (Mm) | LL (Mm) | AR (Mm) | QS (Mm) |
|---------------|---------|---------|---------|---------|
| Height difference between the h and k peaks | 0.7 | 0.3 | 0.9 | 1.0 |
| Height difference between triplet peaks | 1.1 | 0.1 | 0.4 | 0.3 |

**Note.** This table shows the chromosphere and TR height differences of five peaks of the Mg II h and k spectrum index for the four regions under discussion (CH, LL, AR, QS).
the number of shifts related to network BPs is more than that for the redshift at internetwork BPs. In general, it can be said that for the redshift at the AR. These values for the CH regions are higher than in the internetwork BPs of the AR. Negative value indicated downward flows and positive value related to upward flows.

As a result, for the analysis of this article, 40 km s\(^{-1}\) has been selected as a value of Doppler velocity (line of sight). Kim et al. (2008) in 2008 stated the phase speed was estimated at 260 to 460 km s\(^{-1}\). In 2009, the phase speed was estimated at 50 to 150 km s\(^{-1}\) by He et al. (2009). Abramov-Maximov et al. (2011) calculated this value to be about 30 to 50 km s\(^{-1}\) and in 2012, Morton et al. (2012) obtained 48 to 325 km s\(^{-1}\) for phase speed.

The results of cross wavelet analysis and phase speed of the AR and CH area, respectively are shown in Table 6, for the Doppler velocity of 40 km s\(^{-1}\) at MgII k and h, and using the height difference obtained for the chromosphere and TR thickness at these two peaks in the previous step. According to the results, the phase speed is from 30 to 800 km s\(^{-1}\) in the AR and from 20 to 500 km s\(^{-1}\) in the CH.

Phase speeds are from 20 to 500 km s\(^{-1}\) in network BPs of the CH area and from 30 to 300 km s\(^{-1}\) at internetwork BPs of the CH area; and phase speeds are from 30 to 800 km s\(^{-1}\) at network BPs of the AR and 40 to 400 km s\(^{-1}\) at internetwork BPs of the AR.

In most of the internetwork BPs with an intensity oscillation of 180 s no high correlation was found in the Doppler velocity of k and h peaks in the period of 300 s. Moreover, this is well seen in the results of the CHs.

In most points, the phase speed in the 180 s period is faster than in the 300 s period, but this is not the case everywhere (ex: point P7).

In general, it can be said that the phase speed in the AR is higher than in the CH area. Also, in general, the phase speed at the network BPs is higher than in the internetwork BPs. In general, it can be said that the phase speed in the AR is higher than in the CH area. Also, in general, the phase speed at the network BPs is higher than in the internetwork BPs.

### 4.3. Filling Factor

The filling factor is one of the most critical factors in calculating energy flux. According to what can be seen in

| Table 6 | Phase Speed |
|---------|-------------|
| BP Area  | Point Category | Period Time (s) | Upward Phase Speed (km s\(^{-1}\)) | Downward Phase Speed |
| Network  | P1          | 64             | 180                     | ...            |
|          | P1          | 180           | 790                     | \(-590\)             |
|          | P1          | 300           | 110                     | ...            |
| Internetwork | P2      | 64             | 100                     | ...            |
|          | P2          | 180           | \(\cdots\)                | \(-280\)      |
|          | P2          | 180           | \(\cdots\)                | \(-400\)      |
|          | P2          | 300           | \(\cdots\)                | ...            |
| Network  | P3          | 64             | 70                      | ...            |
|          | P3          | 180           | 290                     | \(-60\)        |
|          | P3          | 300           | 200                     | ...            |
|          | P3          | 300           | 200                     | ...            |
| Internetwork | P4   | 64             | 60                      | ...            |
|          | P4          | 180           | \(\cdots\)                | \(-70\)       |
|          | P4          | 180           | \(\cdots\)                | \(-150\)      |
|          | P4          | 300           | 150                     | ...            |
| Network  | P5          | 64             | 90                      | ...            |
|          | P5          | 180           | \(\cdots\)                | \(-170\)      |
|          | P5          | 180           | \(\cdots\)                | \(-90\)       |
|          | P5          | 300           | 40                      | ...            |
|          | P5          | 300           | 20                      | ...            |
| Internetwork | P6   | 64             | \(\cdots\)                | \(-40\)       |
|          | P6          | 64             | \(\cdots\)                | \(-40\)       |
|          | P6          | 64             | \(\cdots\)                | \(-40\)       |
|          | P6          | 180           | \(\cdots\)                | \(-60\)       |
| Coronal hole | P7  | 64             | \(\cdots\)                | \(-150\)      |
|          | P7          | 180           | 350                     | ...            |
|          | P7          | 180           | 190                     | ...            |
|          | P7          | 300           | 30                      | ...            |
|          | P7          | 64             | \(\cdots\)                | ...            |
|          | P7          | 74             | \(\cdots\)                | \(-130\)      |
|          | P7          | 180           | 90                      | ...            |
|          | P7          | 180           | 30                      | ...            |
|          | P7          | 300           | \(\cdots\)                | ...            |

**Note.** The calculated phase speed for the BPs of the QS and AR is given in this table. BPs P1 to P5 are related to the AR and P6 to P9 are related to the CH. All calculations are performed for two groups of time periods and several time intervals with high accuracy. The negative phase difference values mean lower currents and positive values are related to upward currents.

### Table 7 | Average Phase Speed |
|-------------------|---------------------|
| BP Area            | Period Time (s) | Upward Phase Speed (km s\(^{-1}\)) | Downward Phase Speed |
| Network            | 64               | 80                      | ...            |
|                    | 180              | 540                     | \(-320\)      |
|                    | 300              | 160                     | ...            |
| Active area        | 64               | 70                      | ...            |
|                    | 180              | \(\cdots\)                | \(-220\)      |
|                    | 300              | 150                     | ...            |
| Internetwork       | 64               | 90                      | \(-40\)       |
|                    | 180              | \(\cdots\)                | \(-80\)       |
|                    | 300              | 180                     | ...            |
| Coronal hole       | 64               | \(\cdots\)                | \(-140\)      |
|                    | 180              | 140                     | ...            |
|                    | 300              | 30                      | ...            |

**Note.** Average phase speed of coronal hole and active area for the network and internetwork. Related negative value indicated downward flows and positive value related to upward flows.
network and internetwork areas, the most effective coefficients contribute to high-frequency oscillations, followed by 180 s oscillations. The largest share of downward energy flux is related to high-frequency oscillations, followed by 180 s oscillations. In general, it could be said that 300 s oscillations have the largest share in upward energy transfer, followed by high-frequency oscillations. 180 s oscillations contribute the most to the energy return to the lower layers. At internetwork BPs the following holds true: The total downward energy flux is greater than the total upward energy flux. The most enormous share of upward energy flux is associated with 180 s oscillations. The most considerable share of downward energy flux is related to high-frequency oscillations. In general, it can be said that 180 s oscillations have the most significant share in upward energy transfer. High-frequency oscillations have the most immense share in the return of energy to the lower layers.

4.4. Energy Flux

Equation (1) has been used to calculate the energy flux. In this formula, the average phase speed mentioned in Table 7 and the filling factor values corresponding to the desired area according to Table 3 have been used, and Table 9 has been obtained in which the energy values for the BPs of the network and internetwork at CH are presented.

According to the calculated amounts for the energy flux (Table 9), at the network BPs the following holds true:
The total upward energy flux is greater than the sum of the downward energy flux. The largest share of upward energy flux is related to high-frequency oscillations, followed by 300 s oscillations. The largest share of the downward energy flux is related to high-frequency oscillations, followed by 180 s oscillations.

5. Summary and Results

The propagation of disturbances along the axis of BPs can be deduced when observations are performed at different heights in the TR. Then the phase speed can be estimated from the phase difference (vice versa) between Doppler velocity oscillations at different heights. Papushov & Salakhutdinov (1994) found the phase differences of fluctuations at different heights and then concluded that the propagation speeds should be larger than 300 km s\(^{-1}\). De Pontieu et al. (2007) used Hinode/Solar Optical Telescope (SOT) observations and has stated that some of partially standing waves have upward and downward propagation behavior with phase speed of...
Figure 7. Point 1 (P1)—first row: Doppler velocity time slice diagram at k3 peak of Mg II spectral line core. In this diagram, the speeds are shown in blue, white, and red form, and from $-40$ to $+40$ km s$^{-1}$. Second row—right: global wavelet spectrum of Doppler velocity of k3 peak of Mg II spectral line core. Second row—left: Doppler velocity wavelet analysis at k3 peak of Mg II spectral line core. Values normalized to mean value, with blueish color depicting lower values and yellowish color depicting higher ones. Third row: Doppler velocity time slice diagram at h3 peak of Mg II spectral line core. In this diagram, the speeds are shown in blue, white, and red form, and from $-40$ to $+40$ km s$^{-1}$. Fourth row—right: global wavelet spectrum of Doppler velocity of h3 peak of Mg II spectral line core. Fourth row—left: Doppler velocity wavelet analysis at h3 peak of Mg II spectral line core. Values normalized to mean value, with blueish color depicting lower values and yellowish color depicting higher ones. Fifth row: cross wavelet analysis of Doppler velocities of k3 and h3 peak of Mg II spectral line core.
50–200 km s\(^{-1}\). Gošić et al. (2018) illustrated that fine BPs internetwork magnetic fields play an essential role as a heating agent. They gave shreds of evidence of internetwork magnetic elements cancellations in the photosphere that can make transient brightness in the chromosphere and TR. These bright structures might be the signature of energy release and heating, probably driven by the magnetic reconnection of internetwork field lines.

In this research, one of the most critical wave characteristics, namely phase speed, in the chromosphere is investigated. For

**Figure 8.** Point 2 (P2)—same as Figure 6 explanation but for P2.
this purpose, the chromosphere and TR thickness was calculated using the Mg II spectrum and the phase speed between the two peaks Mg II k and h was calculated. In this paper, the phase speed of the network and internetwork BPs, at the AR and the CH, has been studied separately. According to the results, the phase speed in the network BPs is higher than the internetwork ones and it also seems that the phase speed at the active areas is higher.

Figure 9. Point 3 (P3)—same as Figure 6 explanation but for P3.
We suggest that the Doppler shift of the central lines depression correlates strongly with the vertical velocity, which is typically placed in order of 0.5 Mm below the TR. By combining the Doppler shifts of the Mg II k and h lines we can retrieve the sign of the velocity gradient just below the TR. Leenaarts et al. (2013) found that the central line intensity and the structure height are anticorrelated with each other, and this anticorrelation is more divulged in a few square Mm. This

Figure 10. Point 4 (P4)—same as Figure 6 explanation but for P4.
intensity can be used to measure the changes of TR height. The peak intensity of the emission lines has a high correlation with the temperature of the formation height. As a result, these peaks are characteristic for temperature detection and the velocity gradient in the upper chromosphere that is related to the difference in the wavelength of the blue and red peaks. So, Mg II k and h lines are excellent markers for upper chromosphere and below TR; this method is only possible for Mg II.
**Figure 12.** Point 6 (P6)—same as Figure 6 explanation but for P6.
Figure 13. Point 7 (P7)—same as Figure 6 explanation but for P7.
Figure 14. Point 8 (P8)—same as Figure 6 explanation but for P8.
Figure 15. Point 9 (P9)—same as Figure 6 explanation but for P9.
lines. Also, these lines are suitable for detecting temperature and velocity in the middle chromosphere. For the reasons mentioned, many investigations related to the velocities and temperatures of the chromosphere have been done using Mg lines (e.g., Tavabi et al. 2022; Sadeghi & Tavabi 2022).

Zaqarashvili et al. (2010) found that the propagation of the actual oscillations is rather challenging to detect with the relative Fourier phase differences between oscillations at different levels indicating the propagation speed of $>110$ km s$^{-1}$. In some oscillations, which could be related to standing patterns, waves seem to be at higher phase speeds ($>300$ km s$^{-1}$).

In conclusion, in this work, we analyzed spectral observations of Mg II line emissions, for the first time at subarcsecond resolution accessible with IRIS, particularly focusing on the Doppler shifts of the emission of different regions and showing broad distributions of Doppler shifts. These characteristics are primarily confined to the TR and show shifts caused by episodic heating in the lower solar atmosphere. The viability of the phase speed of wave as a heating mechanism relies upon the efficient dissipation and thermalization of the wave energy, with direct evidence remaining elusive until now. Here we provide and implemented the first observational evidence of phase speed heating the TR.

Finally, we suggest that the Doppler velocity oscillations propagate the longitudinal wave in the stratified TR along the axis of magnetic BPs (Sadeghi & Tavabi 2022), which are excited by p-modes buffeting in network and internetwork positions in the CH and AR.

The mean Doppler velocities of network BPs undergo oscillations with periods of 180 and 300 s at the CH and the phase speed is about 130 km s$^{-1}$; Doppler velocities of internetwork BPs undergo oscillations with periods of 180 and 300 s at the CH and the phase speed is about 80 km s$^{-1}$; Doppler velocities of network BPs undergo oscillations with periods of 180 and 300 s at the AR and the phase speed is about 340 km s$^{-1}$; Doppler velocities of internetwork BPs undergo oscillations with periods of 180 and 300 s at the AR and the phase speed is about 180 km s$^{-1}$.

The Doppler velocity waves propagation carries almost all of the energy of initial perturbations. In contrast, the energy in wake oscillations is much smaller than other ones. Therefore, the energy carried into the TR and corona by longitudinal waves with the remarked phase speeds can be much higher than is estimated by observed oscillations. More observations and numerical/analytical works are needed to look further into this problem. It seems that the estimated energy flux of this mode provides the energy required to heat the solar corona, taking into account the dissipated.

The energy flux estimation gives us much information about how energy is transferred between the solar atmosphere’s layers and how they heat up. To calculate this critical component, it is necessary to obtain the filling factor in the study area. In this study, we obtained the filling factor values for the CH region and oscillations of 64 (high frequencies), 180, and 300 s. Using the values of the filling factor, the contribution of each of the oscillations in the energy supply of the higher layers has been determined.

The mean Doppler velocities of network BPs undergo oscillations with periods of 180 and 300 s and high frequencies at the CH and the net energy flux is about $7380$ W/m$^2$.

Doppler velocities of internetwork BPs undergo oscillations with periods of 180 and 300 s at the CH and the net energy flux is about $−1560$ W/m$^2$ (negative values mean the return of energy to the lower layers and positive values mean the transfer of energy to the higher layers).

An important point to note at the end is that all calculations have been made for energy flux at Doppler velocities of 40 km s$^{-1}$, and by calculating the share of other velocities it can increase the net flux, and this increase probably has a value about below 20%.

Finally, it should be emphasized that the typical amount for energy flux at a Doppler velocity has been calculated of the dominant Doppler peak to be around 40 km s$^{-1}$ in the TR, and this value must be integrated all over the other velocities; it can significantly increase the energy net flux.

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Wavelet software was provided by C. Torrence and G. Compo, and is available at http://paos.colorado.edu/research/wavelets/.

Data availability

The IRIS data that were used in this article are available at https://iris.lmsal.com.

The AIA and HMI data of SDO are publicly available at http://jsoc.stanford.edu/. Cross Wavelet and Wavelet Coherence Toolbox were provided by A. Grinsted, J. C. Moore, and S. Jevrejeva, and is available at http://grinsted.github.io/wavelet-coherence/.

Wavelet software that was used for wavelet analysis is available at http://paos.colorado.edu/research/wavelets/.

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