Spectroscopic Evidence of Alfvén Wave Damping in the Off-limb Solar Corona

G. R. Gupta

Inter-University Centre for Astronomy and Astrophysics, Post Bag-4, Ganeshkhind, Pune 411007, India; girjesh@iucaa.in

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Abstract

We investigate the off-limb active-region and quiet-Sun corona using spectroscopic data. The active region is clearly visible in several spectral lines formed in the temperature range of 1.1–2.8 MK. We derive the electron number density using the line ratio method, and the nonthermal velocity in the off-limb region up to the distance of 140 Mm. We compare density scale heights derived from several spectral line pairs with expected scale heights per the hydrostatic equilibrium model. Using several isolated and unblended spectral line profiles, we estimate nonthermal velocities in the active region and quiet Sun. Nonthermal velocities obtained from warm lines in the active region first show an increase and then later either a decrease or remain almost constant with height in the far off-limb region, whereas nonthermal velocities obtained from hot lines show consistent decrease. However, in the quiet-Sun region, nonthermal velocities obtained from various spectral lines show either a gradual decrease or remain almost constant with height. Using these obtained parameters, we further calculate Alfvén wave energy flux in both active and quiet-Sun regions. We find a significant decrease in wave energy fluxes with height, and hence provide evidence of Alfvén wave damping. Furthermore, we derive damping lengths of Alfvén waves in the both regions and find them to be in the range of 25–170 Mm. Different damping lengths obtained at different temperatures may be explained as either possible temperature-dependent damping or by measurements obtained in different coronal structures formed at different temperatures along the line of sight. Temperature-dependent damping may suggest some role of thermal conduction in the damping of Alfvén waves in the lower corona.

Key words: Sun: corona – Sun: UV radiation – turbulence – waves

1. Introduction

Heating of the solar atmosphere and acceleration of solar wind remain two of the most puzzling problems in solar and space physics. There have been several theories proposed to explain the phenomena; however, to identify any one dominant process is extremely difficult to do. For details, see Parnell & De Moortel (2012), De Moortel & Browning (2015), and references therein for current developments in the field. Most of the models proposed so far have been attributed to either dissipation of magnetohydrodynamics (MHD) waves or magnetic reconnection. Among the several proposed ideas, the role of wave turbulence in the heating of the solar corona and acceleration of solar wind is one of the best-studied models (see recent reviews by Arregui 2015; Cranmer et al. 2015). Alfvén (1942) first suggested the existence of electromagnetic-hydrodynamic waves in the solar atmosphere and its importance in the heating of the solar corona (Alfvén 1947). This led to the wave-heating model of the solar corona. In this model, convective motions at the footpoints of magnetic flux tubes are assumed to generate wave-like fluctuations that propagate up into the extended corona (Cranmer & van Ballegooijen 2005; Suzuki & Inutsuka 2005). These fluctuations are often assumed to partially reflect back down toward the Sun, develop into strong MHD turbulence, and dissipate gradually (Cranmer et al. 2007; Verdini et al. 2010). Recently, Van Ballegooijen et al. (2011) developed a three-dimensional MHD Alfvén wave turbulence model to explain the heating of both the solar chromosphere and corona in the coronal loop. Another model used to explain coronal heating is the nanoflare heating model (see the recent review by Klimchuk 2015). In this model, random photospheric motions and flows lead to twisting and braiding of coronal field lines. This results in build-up of magnetic stress, and thus, leads to the release of energy in the form of impulsive heating events called nanoflares (Parker 1988).

In order to understand the wave-heating mechanism in the solar atmosphere, the detection and observations of propagation and dissipation of waves are essential. Tomczyk et al. (2007) and McIntosh et al. (2011) reported the ubiquitous presence of outwardly propagating Alfvénic (transverse) waves in the solar corona. Propagating Alfvénic waves were also found in the polar region (Gupta et al. 2010; Morton et al. 2015). Comprehensive reviews exist on the detection of propagating waves in the solar atmosphere, e.g., Banerjee et al. (2011), De Moortel & Nakariakov (2012), and Jess et al. (2015). In recent studies, evidence of damping of propagating waves have also been reported (Gupta 2014; Krishna Prasad et al. 2014; Morton et al. 2014). Signatures of Alfvén waves can also be found in studies of spectral line profile broadening in the solar corona (e.g., Banerjee et al. 2009; Jess et al. 2009). Alfvénic wave motions are transverse to the direction of propagation. In case of field lines aligned in the plane of sky, plasma motions due to Alfvénic waves will either be directed toward or away from the line of sight. In the off-limb corona, several spatially unresolved structures with different phases of oscillations may be present along the line of sight. These unresolved wave motions can lead to nonthermal broadening of spectral line profiles. Thus, the observed nonthermal broadening of spectral line profiles in the corona will be proportional to Alfvén wave amplitude, e.g., Moran (2001).

There are numerous studies devoted to measuring the off-limb nonthermal broadening of spectral lines to search for any wave activity. Hassler et al. (1990) performed the first observations of high-temperature line profiles in the solar off-limb region using sounding rocket experiments. They found that the line width increased with height above the limb and interpreted this as a signature of propagating hydromagnetic...
waves in the solar corona. Later, more studies were carried out using the space-based SUMER instrument on board SOHO. Using SUMER, Doyle et al. (1998) and Banerjee et al. (1998) found that the nonthermal line width increased with off-limb height and the associated density decreased. Their results were in excellent agreement with the predictions for outwardly propagating undamped Alfvén waves. Harrison et al. (2002) performed a similar analysis on the off-limb part of the quiet-Sun corona using the CDS instrument on board SOHO. They found that the line width narrowed with height and interpreted this as indication of wave dissipation in a closed loop system in the low corona. Banerjee et al. (2009) performed a similar analysis on the polar plume and interplume region using the Extreme-Ultraviolet Imaging Spectrometer (EIS; Culhane et al. 2007) on board Hinode (Kosugi et al. 2007). They found signatures of outwardly propagating undamped linear Alfvén waves within 1.1 \( R_\odot \). Recently, Bemporad & Abbò (2012) and Hahn et al. (2012) measured the nonthermal line width to be up to 1.4 \( R_\odot \) in the open magnetic field of the polar regions using EIS/Hinode. They found signature of damping of Alfvén waves beyond 1.1–1.14 \( R_\odot \). Lee et al. (2014) investigated a cool loop and dark lane over an off-limb active region and obtained basic plasma parameters as a function of height above the limb. They found a slight decrease in the nonthermal velocity along the cool loop whereas they found a sharp fall along the dark lane. They attributed these findings to wave damping. Hahn & Savin (2014) also measured the energy and dissipation of Alfvénic waves in the quiet-Sun region.

Recently, Van Ballegooijen et al. (2011) developed a 3D MHD model of Alfvén wave turbulence to explain the heating of the solar chromosphere and corona in the coronal loop. This model has attracted a lot of attention from the community to look for such signatures (e.g., Asgari-Targhi et al. 2014). In this work, we focus on the off-limb active-region loop system and quiet-Sun corona to study the propagation of Alfvén waves with height and search for any signature of their damping over a wide range of temperature. The Alfvén wave energy flux density is given by (e.g., Moran 2001)

\[
E_D = \rho \xi^2 V_A = \frac{\rho}{4\pi} \xi^2 B, \tag{1}
\]

where \( \rho \) is mass density (\( \rho = m_p N_e \)), \( m_p \) is proton mass, and \( N_e \) is electron number density, \( \xi \) is Alfvén wave velocity amplitude, and \( V_A \) is the Alfvén wave propagation velocity given as \( B/\sqrt{4\pi \rho} \). Therefore, total wave energy flux crossing a surface area \( A \) will be given by

\[
E_F = \frac{1}{4\pi} j m_p V_A \xi^2 B A. \tag{2}
\]

Therefore, the total Alfvén wave energy flux depends on the electron number density, wave amplitude, magnetic field, and area of cross-section. In this paper, our main focus is to estimate the total wave energy flux with height in the off-limb solar corona, and thus to find signatures of wave damping. For this purpose, we identified a unique set of good spectroscopic data covering the off-limb active region and quiet Sun observed by EIS/Hinode. The data cover various spectral lines formed over a wide range of temperatures. Previous studies were mainly carried out with a few spectral lines formed at a very similar temperature, e.g., Fe XII, and Fe XIII. Therefore, the current study provides a unique opportunity to carry out such analysis for coronal structures formed over a wide range of temperatures. This may also enable us to find any possible existence of temperature dependence. Related details of the observations are described in Section 2. We employ spectroscopic methods, which are described in Sections 3.1 and 3.2, to obtain the electron number density and nonthermal velocity, respectively. In Section 3.3, we describe the calculation of the Alfvén wave energy flux using the obtained parameters. The obtained results are discussed in Section 4, and the final summary and conclusions are provided in Section 5.

2. Observations and Data Analysis

The off-limb active region AR 10978 was observed by EIS/Hinode on 2007 December 17. The EIS observations were carried out with a 2″ slit and exposure time of 45 s. Observations were performed over the wavelength range of 180–204 \( \AA \) and 248–284 \( \AA \). Raster scan started at 10:42:20 UT and completed at 13:02:17 UT and covered a field of view of 360″ x 512″. This data set was previously analyzed by O’Dwyer et al. (2011) to study the electron density and temperature structure of a limb active region. We followed the standard procedures for preparing the EIS data using IDL routine EIS_PREP,1 available in the Solar Software (Freeland & Handy 1998). Recently, Brooks & Warren (2016) and Testa et al. (2016) showed that absolute calibration of EIS data leads to a systematic overestimation of spectral line widths for most of the pixels along the slit. Thus, for the purpose of measuring line widths, we obtained EIS spectra in the data number unit by applying the EIS_PREP routine with the /noabs keyword. Moreover, we also obtained EIS spectra in physical units (erg \( cm^{-2} s^{-1} sr^{-1} \)) to further perform electron number density diagnostics. This routine also provides error bars on the obtained intensities. In addition, there also exists a 22% uncertainty in the observed intensity based on the pre-flight calibration of EIS (Lang et al. 2006). All the EIS spectral line profiles were fitted with a Gaussian function using EIS_AUTO_FIT.2 The routine also provides 1σ error bars on the fitted parameters. Comparison between both types of spectra reconfirms the systematic overestimation of line widths from absolutely calibrated data as recently reported by Brooks & Warren (2016) and Testa et al. (2016). However, the magnitude of this systematic overestimation of line widths was found to be very small in the current data set. As EIS sensitivity is evolving over time, absolutely calibrated data (in physical units) and related errors were further recalibrated using the method of Warren et al. (2014). There exist spatial offsets in the solar-X and solar-Y directions between images obtained from different wavelengths. These offsets were corrected with respect to the image obtained from the Fe XII 195.12 \( \AA \) spectral line. Figure 1 shows the intensity map of the observed off-limb active region obtained from the Fe XII 195.12 \( \AA \) line. The observed active region is very bright and has several saturated image pixels at a few locations.

To identify spectral line wavelengths and corresponding peak formation temperatures, all of the atomic data used in this study are taken from the CHIANTI atomic database (Dere et al. 1997; Del Zanna et al. 2015). To perform line width

1 ftp://sohoftp.nascom.nasa.gov/solarsoft/hinode/eis/doc/eis_notes/01_EIS_PREP/eis_swnote_01.pdf
2 ftp://sohoftp.nascom.nasa.gov/solarsoft/hinode/eis/doc/eis_notes/16_AUTO_FIT/eis_swnote_16.pdf
3 ftp://sohoftp.nascom.nasa.gov/solarsoft/hinode/eis/doc/eis_notes/03_GRATING_DETECTOR_TILT/eis_swnote_03.pdf
analysis, we identified several unblended and isolated spectral lines with good signal strength as highlighted by Young et al. (2007) (see Table 1). Although there exist some blending in the Fe XIV 274 Å and Fe XV 284 Å lines, their contribution to the active-region conditions can safely be ignored. Lines are chosen in such a way as to get good coverage over the temperature range. The contribution function of the selected spectral lines was calculated using CHIANTI v.8 (Del Zanna et al. 2015) at a constant electron number density $N_e = 10^9 \text{ cm}^{-3}$. The obtained contribution function curves are plotted in Figure 2. The peak formation temperatures of all the selected lines are also provided in Table 1. We identify all of the spectral lines formed below a temperature of 2 MK as warm lines whereas those formed above 2 MK are identified as hot lines. We also identified several density-sensitive lines and utilized them only for the purpose of deriving the electron number density.

In Figure 3, we plot monochromatic intensity maps of the off-limb active region obtained from different emission lines formed over the temperature range of 1.1–2.8 MK. The intensity maps clearly show that structures in the active region are not well defined as discrete loops; instead, emissions are more likely diffuse in nature without any sharp boundaries. Diffuse emissions in the Fe X–Fe XVI lines observed from the active region are real. Such diffuse emissions were also highlighted by several authors in the past (e.g., O’Dwyer et al. 2011). Here, we show the diffuse nature of the active region with several emission lines formed over 1.1–2.8 MK.

To study the variation of several physical parameters with height, we chose several structures and stripes in the off-limb active region and quiet Sun. Although the active region is diffuse in nature, we can still identify some bright loop-like structures extending far into the corona from the Fe XII 192.394 Å intensity map. We traced and analyzed several such structures. Here, we present the result from one such structure, which was traced up to a very far off-limb distance. The traced stripe is named AR1. Furthermore, to get the average behavior of the active region, we binned over the entire active-region data in the solar-Y direction. Similarly, we also binned over a small quiet-Sun region in the solar-Y direction to study the quiet Sun. Boxes chosen to obtain the average data are labeled AR2 and QS. We also traced another stripe parallel to AR1 in the quiet-Sun region only for the purposes of a background study. All the chosen stripes and boxes are shown in Figure 3.

As the selected spectral lines are isolated and unblended, we fitted all the profiles with a single Gaussian function. In Figure 4, we show examples of the spectral line profiles and fitted Gaussian profiles. Profiles were obtained at the off-limb distance of 61 Mm along AR1, AR2, and QS. From the plots, it

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**Table 1**

| Ion   | Wavelength (Å) | $T_{\text{peak}}$ (MK) |
|-------|----------------|------------------------|
| Fe X  | 184.537        | 1.12                   |
| Fe XI | 180.401, 182.167 | 1.37                   |
| Si X  | 258.374*       | 1.41                   |
| S X   | 264.231        | 1.55                   |
| Fe XII| 192.394, 196.640 | 1.58                   |
| Fe XIII| 196.525*, 202.044 | 1.78                   |
| Fe XIV| 264.789*, 274.204 | 2.00                   |
| Fe XV | 284.163*       | 2.24                   |
| Fe XVI| 262.976        | 2.82                   |

**Notes.** Lines marked with asterisks (*) are density-sensitive lines and used only to calculate the electron number densities.  
* Wavelengths and peak formation temperatures are taken from the CHIANTI database.  
* Blended with Si VII 274.180 Å.  
* Blended with Al IX 284.042 Å.

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**Figure 1.** Intensity map of the off-limb active region and quiet Sun in the Fe XII 195.12 Å spectral line rastered by EIS/Hinode on 2007 December 17. The solid white line indicates the location of the solar limb.

**Figure 2.** Contribution function of spectral lines selected for detailed analysis of the off-limb active- and quiet-Sun regions recorded by EIS/Hinode (see also Table 1).

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3
is clear that all the profiles are symmetric and can be well represented by a single Gaussian function.

One of the factors that may affect our analysis would be contamination from instrumental scattered or stray light. The minimum stray-light contribution above the dark current is found to be around $2\%$ of the total on-disk counts for that respective line. We chose a sufficient box size to calculate the average counts from each spectral line in the on-disk part of Sun. As stray-light contamination in the off-limb corona will be simply $0.02$ times the average counts, we obtained the fraction of stray-light contribution along all the stripes for all of the lines. As intensity drops off with height in the off-limb corona, the stray-light contribution increases with height. We found stray-light contributions to be less than $8\%$ up to the off-limb distance of $\approx 140$ Mm along AR1 and AR2 in all spectral lines except for Fe XVI 263 Å. These contributions were obtained after using the $2\%$ weighting of on-disk counts. For the Fe XVI 263 Å spectral line, stray-light contributions were below $9\%$ up to the distance of $100$ Mm. Beyond that distance, the contribution increases sharply to about $20\%$ and $35\%$ along AR1 and AR2, respectively. For the quiet-Sun region QS, stray-light contributions were less than $15\%$ up to a very far distance ($\approx 125$ Mm) in most of the spectral lines. Stray-light contributions in the Fe X 185 Å, Fe XIV 274 Å, and Fe XV 284 Å lines increase sharply to above $40\%$ for distances beyond $130$ Mm, whereas that in Fe XVI 262.976 Å goes beyond $100\%$ for most of the distances along QS. This may indicate that the signal in the Fe XVI 262.976 Å line along QS is mainly from scattered light. Near the limb, stray-light contributions for all the stripes are much smaller ($<3\%$ for heights $<80$ Mm and $<90$ Mm along AR1 and AR2, respectively, whereas $<5\%$ for heights $<50$ Mm for QS). As noted by Hahn et al. (2012), stray-light contaminations start affecting line-width measurements only if their contributions are more than $45\%$. In the current analysis, as stray-light contributions are found to be very small, its effects are thus almost insignificant in the line-width measurements. Results obtained in the present analysis are mainly derived from heights where stray-light contaminations are very small for most of the spectral lines ($<8\%$ for distances up to $\approx 140$ Mm)

Figure 3. Monochromatic intensity maps of the off-limb active region and quiet Sun obtained in different wavelengths using EIS/Hinode (as labeled). Dashed white lines and boxes on each panel indicate the off-limb locations (active regions AR1, AR2, and quiet Sun QS, BG) chosen for detailed analysis. The solid white line in each panel indicates the location of the solar limb.
along AR1 and AR2, and <15% for distances up to ≈125 Mm along QS.

3. Results

Per Equation (2), the Alfvén wave energy flux is proportional to $N_e A e^2$. We describe the estimation of the electron number density and wave velocity amplitude in the following subsections.

3.1. Intensity, Density, and Emission Measure

In Figure 5, we plot the variation with height of the intensity obtained from selected spectral lines along the active regions AR1 and AR2, and the quiet Sun QS. Associated error bars are also plotted with the data points. From the plots, it is clear that the data set has good signal strength in all selected spectral lines in the off-limb region of the solar corona. This makes it suitable for estimating the electron number density to calculate the total Alfvén wave energy flux with height.

Electron number densities obtained from various spectral line pairs in the corona can be compared using the hydrostatic equilibrium model. This has been done in the past with imaging observations using the Transition Region and Coronal Explorer (TRACE; e.g., Aschwanden et al. 1999), and recently with spectroscopic observations using EIS/Hinode (e.g., Lee et al. 2014; Gupta et al. 2015).

The electron number density profile in hydrostatic equilibrium is given by

$$N_e(h) = N_e(0) \exp\left(-\frac{h}{\lambda(T_e)}\right),$$

where $\lambda$ is the density scale height given by

$$\lambda(T_e) = \frac{2k_B T_e}{\mu m_H g},$$

where $k_B$ is the Boltzmann constant, $T_e$ is the electron temperature, $\mu$ is the mean molecular weight ($\approx 1.4$ for the solar corona), $m_H$ is the mass of the hydrogen atom, and $g$ is the acceleration due to gravity at the solar surface (see, e.g., Aschwanden et al. 1999).

Moreover, observationally measured quantities, such as the intensity of an optically thin emission line, depend on the electron number density, i.e., $I \propto N_e^\beta$, where $1 < \beta < 3$ and the value of $\beta$ depends on whether the given line is allowed, forbidden, or intersystem (Mason & Monsignori Fossi 1994).

In this study, we have chosen only allowed lines to perform the line-width analysis. Some density-sensitive forbidden lines were also chosen to calculate the electron number density (see...
In Figure 5, we plot the variation with height of the intensity obtained from all of the spectral lines along the AR1, AR2, and QS stripes. Since the data set covers the active- and quiet-Sun regions over a wide range of wavelengths, we identified several density-sensitive line pairs formed over a range of temperatures. We selected the Fe XI $\lambda 182.167/\lambda 180.401$, Si X $\lambda 258.374/\lambda 261.056$, Fe XII $\lambda 196.640/\lambda 192.394$, Fe XIII $\lambda 196.525/\lambda 202.044$, and Fe XIV $\lambda 264.789/\lambda 274.204$ line pairs to obtain the electron number density (Young et al. 2007). In performing density and temperature diagnostics on the active-region loops, background subtraction plays an important role (e.g., Del Zanna & Mason 2003). O’Dwyer et al. (2011) previously analyzed the current data set and used the quiet-Sun region to study the background emission. We follow the same strategy and use the intensity along the quiet-Sun stripes to perform background subtraction along the active-region stripes. Therefore, we use the quiet-Sun stripes BG and QS to subtract background emission from the active-region stripes AR1 and AR2, respectively (stripes are shown in Figure 3). All plasma diagnostics are performed over these background-subtracted intensities.

Table 1). In Figure 5, we plot the variation with height of the intensity obtained from all of the spectral lines along the AR1, AR2, and QS stripes.

Since the data set covers the active- and quiet-Sun regions over a wide range of wavelengths, we identified several density-sensitive line pairs formed over a range of temperatures. We selected the Fe XI $\lambda 182.167/\lambda 180.401$, Si X $\lambda 258.374/\lambda 261.056$, Fe XII $\lambda 196.640/\lambda 192.394$, Fe XIII $\lambda 196.525/\lambda 202.044$, and Fe XIV $\lambda 264.789/\lambda 274.204$ line pairs to obtain the electron number density (Young et al. 2007). In performing density and temperature diagnostics on the active-region loops, background subtraction plays an important role (e.g., Del Zanna & Mason 2003). O’Dwyer et al. (2011) previously analyzed the current data set and used the quiet-Sun region to study the background emission. We follow the same strategy and use the intensity along the quiet-Sun stripes to perform background subtraction along the active-region stripes. Therefore, we use the quiet-Sun stripes BG and QS to subtract background emission from the active-region stripes AR1 and AR2, respectively (stripes are shown in Figure 3). All plasma diagnostics are performed over these background-subtracted intensities.

In Figure 6, we plot the variation with height of the electron number density derived from selected spectral line pairs along AR1, AR2, and QS. The plots show that as height increases, the electron number density decreases; however, the corresponding error bar increases with height. Some of the lines in the quiet-Sun region show estimates with larger error bars. Near the active-region limb, electron number densities were estimated to be of the order of $>10^9$ cm$^{-3}$, which drops to around $10^8$ cm$^{-3}$ in the far off-limb region. Densities obtained from the Fe XI and Fe XII line pairs show almost similar numbers, whereas those obtained from the Fe XIII and Si X line pairs show similar values. Near the limb region, densities from the Fe XI and Fe XII pairs show consistently larger values than those from the Fe XIII and Si X pairs. However, they all seem to converge toward similar values beyond the distance of 80 Mm ($<5 \times 10^8$ cm$^{-3}$) and 95 Mm ($<4.5 \times 10^8$ cm$^{-3}$) along AR1 and AR2, respectively. Densities estimated from the Fe XIV line pair are lower compared to other pairs and also falls off more rapidly with height in both AR1 and AR2.

In the quiet-Sun region, we found the number densities to be lower than those in the active region. In this case, densities estimated from the Fe XII and Fe XIII line pairs converge to similar values beyond 45 Mm ($<1.6 \times 10^8$ cm$^{-3}$). However,
near the limb, densities obtained from the Fe XII pair are higher than those from the Fe XIII pair. Densities obtained from the Si X pair are higher than those estimated from the Fe XII and Fe XIII pairs. Densities estimated from the Fe XI and Fe XIV pairs near the limb are comparatively higher than those obtained from other line pairs but drops off very rapidly with height.

We fitted the electron number density variation with height along AR1, AR2, and QS with the exponential function $N_e = N_0 \exp(-h/H_d) + c$ using MPFIT routines (Markwardt 2009). The fits provide density scale heights $H_d$ at different temperatures obtained from different spectral line pairs (see Table 2). The expected electron density scale heights $\lambda(T_e)$ at different temperatures according to the hydrostatic equilibrium model (see Equation (4)) are also provided in the table. Comparison between the two density scale heights indicate that both the active- and quiet-Sun regions are basically underdense, with few exceptions from the quiet-Sun region.

As active-region and quiet-Sun stripes were observed over a range of temperature, we employed the emission measure (EM) loci technique to examine the thermal structure of different stripes as a function of off-limb height. Several EM loci plots were constructed at different heights along the active-region AR1 and AR2, and quiet-Sun QS stripes. In Figure 7, we present sample EM loci plots obtained at the height of 55 Mm above the off-limb region. From the plots, it is clear that plasma along the line of sight is not isothermal at that height. Based on EM loci plots, the distribution of plasma along all of the stripes were found to be multithermal at all of the heights. These results are in good agreement with the findings of O’Dwyer et al. (2011), who analyzed the same data set previously. They found plasma in the active region to be multithermal at different distances from the limb. Similarly, Warren et al. (2008) also studied isolated coronal loops from the same active region when observed on-disk and found them not to be isothermal. Thus, based on current and previous studies, plasma along the different active-region stripes can be considered multithermal. This may indicate that emission in

![Figure 6](image_url)

Figure 6. Electron number density variation with height along the active regions AR1 and AR2, and the quiet Sun QS obtained from different density-sensitive spectral line pairs as labeled. The overplotted solid lines represent the exponential decay profile fit to obtain density scale heights from various spectral line pairs (see also Table 2).

| Ion   | Wavelength (Å) | $T_{peak}$ (MK) | Hydrostatic height (Mm) | AR1       | AR2       | QS        |
|-------|----------------|-----------------|-------------------------|-----------|-----------|-----------|
| Fe XI | 182.167/180.401| 1.37            | 63.02                   | 24.86 ± 0.31 | 34.22 ± 0.26 | 27.13 ± 0.98 |
| Si X  | 258.374/261.056| 1.41            | 64.98                   | 39.84 ± 2.15 | 53.61 ± 2.25 | 78.12 ± 9.91 |
| Fe XII| 196.640/192.394| 1.58            | 72.91                   | 26.98 ± 0.36 | 28.54 ± 0.20 | 38.70 ± 0.66 |
| Fe XIII| 196.525/202.044| 1.78            | 81.80                   | 55.23 ± 1.44 | 63.44 ± 0.22 | 90.61 ± 5.48 |
| Fe XIV| 264.789/274.204| 2.00            | 91.78                   | 41.37 ± 0.56 | 43.53 ± 0.32 | 14.00 ± 0.96 |
different lines are coming from either a single coronal structure formed over a wide range of temperatures or there exist multiple structures at different temperatures along the line of sight. Moreover, plasma along the off-limb quiet Sun region appears to be nearly isothermal if the contributions from hot lines are excluded. Figure 5 shows that intensities obtained from hot lines along QS are increasing with height near off-limb regions. This may suggest some possible contaminations from a nearby active region in the hot lines.

3.2. Nonthermal Velocity

Nonthermal velocities are an important ingredient for calculating Alfvén wave energy flux. These have been extracted from the observed emission line profiles as follows. The observed FWHM of any coronal spectral line is given by

\[
\text{FWHM} = \left[ 4 \ln 2 \left( \frac{\lambda}{c} \right)^2 \left( \frac{2 k_B T_i}{M_i} + \xi^2 \right) + W_{\text{inst}}^2 \right]^{1/2},
\]

where \( T_i \) is the ion temperature, \( M_i \) is the ion mass, \( \xi \) is the nonthermal velocity, and \( W_{\text{inst}} \) is the instrumental width. The EIS/Hinode instrumental width is not constant and is found to vary with CCD Y-pixel position along the slit.\(^5\) The EIS instrumental width for the 2" slit varies between 64 and 74 mÅ for a downloaded central 512 pixels (starting from pixels 256 to 767). These widths were calculated using the IDL routine EIS_SLIT_WIDTH provided by the EIS team. Instrumental widths were then subtracted from the FWHM of the spectral lines accordingly. We further calculated nonthermal components by subtracting the thermal components from each spectral line. The thermal components were calculated after assuming the ion temperatures to be equal to the peak formation temperature of the spectral lines as found from the contribution functions (see Figure 2 and Table 1). After subtraction of instrumental width, the line widths were primarily dominated by nonthermal components. Error bars on nonthermal velocities were calculated using errors in the profile fitting, 3 mÅ error in instrumental width, and errors in the assumed thermal temperatures, which were taken to be the half width half maxima of Gaussian fits applied to the contribution functions of the respective spectral lines.

In Figures 8–10, we plot with height the nonthermal velocities (\( \xi \)) obtained from various spectral lines along the active regions AR1 and AR2, and quiet Sun QS, respectively. We also overplot the 20 point running average of data points to visualize the variations on longer spatial scale. Nonthermal velocities obtained from warm lines such as FeX 185 Å, Fe XII 192 Å, and Fe XIII 202 Å show an initial increase from \( \approx 24 \text{ km s}^{-1} \) near the limb to \( \approx 33 \text{ km s}^{-1} \) around the height of 80 Mm, whereas those obtained from SiX 261 Å and SiX 264 Å show an increase from \( \approx 34 \) to \( \approx 39 \text{ km s}^{-1} \) at similar heights along AR1. Beyond these heights, nonthermal velocities either decrease or remain almost constant with some scattered data points.

The variation of nonthermal velocities with height along AR2 also show a pattern similar to that in AR1, but their values are enhanced by \( \approx 2–3 \text{ km s}^{-1} \). This possible enhancement along AR2 could be due to integration taken over a larger spatial scale to deduce the nonthermal velocities. Compared with polar regions (e.g., Banerjee et al. 2009; Bemporad & Abbo 2012), the nonthermal velocities obtained from the Fe XII line in the active regions are consistently smaller in magnitude but shows a sharp increase with height. However, the recent findings of Lee et al. (2014) showed a consistent decrease in nonthermal velocities along the cool loop and dark lane in the off-limb active region. Moreover, nonthermal velocities obtained from hot lines such as FeXV 284 Å and FeXVI 263 Å show a gradual decrease with height. Velocities obtained from the hot FeXV 284 Å line show a decrease from \( \approx 45 \text{ km s}^{-1} \) near the limb to \( \approx 36 \text{ km s}^{-1} \).
Beyond 100 Mm along AR1, whereas those from the Fe XVI 263 Å line show a decrease from ≈38 km s\(^{-1}\) to ≈32 km s\(^{-1}\). The variations obtained from the hot Fe XV 284 Å and Fe XVI 263 Å lines along AR2 again show a pattern similar to that in AR1 with the velocities being again enhanced by ≈2–3 km s\(^{-1}\). Surprisingly, the variations from the warm Fe XI 180 Å line show a pattern similar to that of hot lines whereas those for the Fe XIV 274 Å line show behavior intermediate between hot and warm lines. Singh et al. (2006) performed a line-width study along steady coronal structures using data from the Norikura coronagraph. They found a decrease in the FWHM of the hot Fe XIV 5303 Å line up to the distance of 300″ above the limb, which became constant thereafter. They also found an increase in the FWHM of the warm Fe X 6374 Å line up to the distance of 250″, which remained unchanged further. The FWHM of the intermediate lines (Fe XI 7892 Å and Fe XIII 10747 Å) showed intermediate behavior. Thus, results of the line-width variation with height do indicate some temperature dependence. Findings in this study are almost similar to those of Singh et al. (2006), with some shift in temperature dependence. This shift might be specific to the active regions studied. However, the cause for exceptional behavior of the warm Fe XI 180 Å line in this study is unknown and cannot be speculated at this stage. Recently, Brooks & Warren (2016) surveyed 15 nonflaring on-disk active regions using EIS/Hinode. They measured nonthermal velocities at specific locations in the cores of solar active regions over the temperature range of 1–4 MK. However, they did not find any significant trend with temperature.

In the quiet-Sun region, nonthermal velocities obtained from warm iron lines show consistent decrease with height. Nonthermal velocities obtained from the warm Si X and S X lines show almost constant values of ≈34 km s\(^{-1}\) and ≈36 km s\(^{-1}\), respectively, with height; however, they do show some large scatter around. Nonthermal velocities obtained from the hot Fe XIV and Fe XV lines also show a decrease with height similar to the warm lines. No visible pattern can be inferred from the hot Fe XVI line as the signal in this line in the quiet-Sun region is mostly due to scattered light as mentioned earlier. These findings are similar to those of Harrison et al. (2002), where they studied the spectral line profiles of the warm Mg X 625 Å line from the quiet clean corona. They found a narrowing of the emission lines as a function of height, similar to findings in this study. They attributed the narrowing of the profiles with height to dissipation of wave activity.

**Figure 8.** Variation of nonthermal velocity with height along the active region AR1 obtained from various spectral lines as labeled. Overplotted solid lines in all the panels show a smooth variation of data points obtained using the 20 point running average.
3.3. Alfvén Wave Energy Flux

Alfvén wave energy flux can be calculated using Equation (2). In a flux-tube geometry, $B \times A$ will always be a constant. Because in a constant magnetic field model the cross-sectional area will remain constant, the product will also remain constant. However, in the case of an expanding flux-tube model, $B$ will decrease with height (let us assume an inverse square field dependence), whereas $A$ will increase with squared radius dependence, thus the product of $B$ and $A$ will again be constant (see Moran 2001). Therefore, the total Alfvén wave energy flux will always be proportional to $\sqrt{N} \xi^2$ in either case. Henceforth, if the total Alfvén wave energy flux is conserved as waves propagate outward, $\sqrt{N} \xi^2$ will remain constant with height. In Figures 11–13, we plot variations of $\sqrt{N} \xi^2$ with height obtained from selected spectral lines along the active regions AR1 and AR2, and quiet Sun QS. As the electron number densities were estimated only from a few spectral line pairs, therefore for the rest of the lines, we choose number densities obtained from line pairs formed at the nearest temperatures. Plots clearly show that the product $\sqrt{N} \xi^2$ decreases with height in all spectral lines in all of the regions. This provides clear evidence of damping of Alfvén wave energy flux with height in the both off-limb active- and quiet-Sun regions. Alfvén wave energy fluxes are found to be $\approx 1.85 \times 10^7 \text{ erg cm}^{-2} \text{s}^{-1}$ near the limb, which decreases to $\approx 0.86 \times 10^7 \text{ erg cm}^{-2} \text{s}^{-1}$ at around the height of 70 Mm as calculated from the Fe XII 192 Å spectral line. To calculate the Alfvén wave energy flux, we assumed a coronal magnetic field strength of 39 G as measured by Van Doorsselaere et al. (2008) using loop oscillations. The calculated Alfvén wave energy fluxes are of similar order of magnitude, which is required to maintain the active-region corona ($\approx 10^7 \text{ erg cm}^{-2} \text{s}^{-1}$ as estimated by Withbroe & Noyes 1977). Moreover, the coronal magnetic field strength can vary by 10 and 33 G as measured by Lin et al. (2000) in two active regions at distances of 0.12 and 0.15 $R_{\odot}$ using the longitudinal Zeeman effect in the Fe XIII 10747 Å spectral line. Therefore, if the assumed magnetic field strength is of the order of 10 G, then the Alfvén wave energy fluxes will be slightly less than the energy flux required to maintain the corona. One thing to be noted here is that although Alfvén waves are getting gradually damped with height, nonthermal velocities obtained from warm spectral lines were initially increasing with height in the active region. This indicates that damping of Alfvén waves can only be inferred from a complete calculation of the total Alfvén wave energy flux with height. Using only nonthermal velocity estimates with height will not serve the purpose.

Figure 9. Same as Figure 8 but for active region AR2.
Upon finding the evidence of damping of Alfvén wave energy flux with height, we further obtain the damping length in all spectral lines covering a range of temperatures. The effect of damping can be calculated by multiplying $e^{-h/D_l}$ with the proportional Alfvén wave energy flux $\xi^2\sqrt{N_e}$, where $D_l$ is termed the “damping length” for the total Alfvén wave energy flux,

$$F_{\text{tot}} \propto \sqrt{N_e} \ \xi^2 e^{-h/D_l},$$

$$F_{\text{tot}} \approx A \ \sqrt{N_e} \ \xi^2 e^{-h/D_l} + B,$$

where $A$ and $B$ are the appropriate constants. Henceforth, we obtained the damping length by fitting the $F_{\text{tot}}$ values in different spectral lines per Equation (7) using MPFIT routines (Markwardt 2009). The derived damping lengths $D_l$ from various spectral lines along the active regions AR1 and AR2, and quiet Sun QS are in the range of 25–170 Mm and provided in Table 3. Bemporad & Abbo (2012) also reported the decay of the Alfvén wave energy flux with height in the polar coronal hole region. However, they performed a linear fit to the decay profile and estimated the decay rates to be $-1.07 \times 10^{-3}$ erg cm$^{-1}$ below 0.03 $R_\odot$, and $-4.5 \times 10^{-5}$ erg cm$^{-1}$ between 0.03 and 0.4 $R_\odot$. The equivalent damping length for the decay rate between 0.03 and 0.4 $R_\odot$ is calculated to be around 95 Mm. They performed measurements using the EIS Fe XII 195 Å spectral line. In this work, the damping lengths obtained from the Fe XII 192 Å lines are in the range of 75–90 Mm in both active- and quiet-Sun regions. This suggests that the damping lengths obtained from both studies are comparable.

4. Discussions

In this work, we found clear evidence of damping of Alfvén waves in the off-limb active- and quiet-Sun regions. Damping lengths were found to be different for different spectral lines formed at different temperatures (see Table 3). We further explore the existence of any temperature dependence on various decay lengths obtained in this study. Henceforth, we analyze the density scale heights and Alfvén wave-damping lengths with the peak formation temperature of their respective spectral lines (see Table 1). We plot the density scale heights obtained from the different line pairs with respect to their peak formation temperature (see the top panels of Figure 14). The density scale heights first increase and later decrease with temperature. However, the density scale height obtained from the Fe XII pair does not follow this trend. Moreover, the hydrostatic scale heights as expected from Equation (4) are also
provided in Table 2. As mentioned earlier, comparison between the two density scale heights indicate that both active- and quiet-Sun regions are basically underdense, with few exceptions from the quiet-Sun region. However, it appears that emissions coming from spectral lines that formed near the temperature of 1.8 MK are closer to hydrostatic equilibrium than those formed in temperatures different from 1.8 MK in the active region. We speculate that this is because the observed region is filled with plasma of temperature nearly 1.8 MK and has a poor supply of other cooler and hotter plasma. This result might be a characteristic of the observed active region, and different active regions might have different temperature distributions.

In the bottom panels of Figure 14, we plot the damping lengths obtained from different spectral lines with respect to their peak formation temperature. The different panels show that the damping lengths first increase and later decrease with temperature. The maximum damping length is attained at around a temperature of 1.78 MK (corresponding to Fe XIII 202 Å) for all of the active-region and quiet-Sun stripes. We would also like to point out that several structures were traced and analyzed as mentioned earlier. Although the decay lengths obtained are not the same, the results followed a similar pattern in all of the analyzed structures. Therefore, the obtained results indicate the measurement of different damping lengths for different temperatures. These results can be interpreted either as temperature-dependent damping of Alfvén waves or measurement of different damping lengths in different coronal structures formed over a wide range of temperatures along the our line of sight.

The possible temperature-dependent damping length of Alfvén waves may indicate that thermal conduction plays some important role in the damping of these waves. However, the role of thermal conduction in the damping of Alfvén waves has not been explored much (e.g., Van Ballegooijen et al. 2011), although it is very well studied for the case of slow magneto-acoustic waves (e.g., De Moortel et al. 2002). The role of thermal conduction in the damping of slow magneto-acoustic waves were recently observed by Gupta (2014) and Krishna Prasad et al. (2014) based on possible (wave) period-dependent damping length. In this study, although we do not have any information on wave period, we have coverage over a wide range of temperatures. The work of De Moortel et al. (2002) suggested that slightly enhanced
Thermal conductivity may explain the observed damping lengths of 40–50 Mm for slow waves. These enhancements in thermal conductivity were later also suggested by Gupta (2014). In this study, the observed damping lengths for Alfvén waves are in the range of 25–170 Mm as obtained from different temperature lines. Henceforth, these results demand detailed investigation into the role of thermal conduction in the damping of Alfvén waves.

Slow magneto-acoustic waves in the solar corona propagate along the field lines with propagation speed of the order of 100 km s\(^{-1}\) and velocity amplitude of the order of 5–10 km s\(^{-1}\). The active region studied in this work is located near the limb and the derived results are mainly focused on off-limb regions. In the off-limb region, magnetic field lines are generally found to be oriented nearly perpendicular to the observer’s line of sight. Therefore, the contribution from the observed Doppler velocities due to the propagation of slow magneto-acoustic waves to the measurement of nonthermal velocities will be minimal. Similarly, studies on the measurement of plasma flows in active-region loops indicate temperature-dependent flow speeds. Del Zanna (2008) and Tripathi et al. (2009) measured absolute flow speeds to be less than 30 km s\(^{-1}\) along the active-region loops using similar spectral lines formed over the temperature range of 0.6–2 MK. They found a decrease in flow speeds with an increase in temperature (redshift to blueshift). Moreover, Brooks & Warren (2011) also measured an average Doppler velocity of \(-22\) km s\(^{-1}\) from the edges of active regions. Generally, loops cross an active region in the east–west direction, so the flows along the off-limb loops will either be directed toward or away from the observer’s line of sight (if loops are not radially directed). This may lead to some enhancements in the line width. However, as velocities in line-width measurements add in quadrature, the contribution of Doppler velocities due to plasma upflows (<10 km s\(^{-1}\), due to the inclination of loops along the line of sight) will again be minimal in nonthermal velocities. Moreover, there might be some enhancement in the nonthermal broadening, due to these factors, but given the range of error bars (2–4 km s\(^{-1}\)), their contribution cannot be quantified. Measurements on AR2, which were obtained after taking the average over the larger spatial length, show enhancements in nonthermal velocities of \(\approx 2–3\) km s\(^{-1}\) as compared to measurements on AR1. This could possibly be the effect of different Doppler-shifted flows present along several different loop structures, which were summed together to obtain the integrated profile, and thus resulted in larger nonthermal velocities. Henceforth, measured

![Figure 12. Same as Figure 11 but for active region AR2.](image-url)
nonthermal velocities along AR2 can only be considered as an upper limit.

As mentioned earlier, the role of thermal conduction in damping of slow magneto-acoustic waves is well known. One possibility in Alfvén wave damping would be that Alfvén wave energy is being transferred to slow magneto-acoustic waves. These slow waves will further get easily dissipated via thermal conduction and will finally show up as temperature-dependent damping of Alfvén waves. Zaqarashvili et al. (2006) studied the wave energy conversion process in the nonlinear ideal MHD framework. They demonstrated that wave energy can be converted from Alfvén waves to slow magneto-acoustic waves near the region of the corona where the plasma $\beta$ approaches unity. As contributions from slow magneto-acoustic waves in current measurements of non-thermal velocities are minimal, only the damping of Alfvén waves can be inferred from the observed nonthermal velocities.

![Figure 13. Same as Figure 11 but for quiet Sun QS.](image)

### Table 3
Damping Lengths Derived from Various Spectral Lines Along the Active Regions AR1 and AR2, and Quiet Sun QS

| Ion  | Wavelength (Å) | $T_{\text{peak}}$ (MK) | $\Delta V_{\text{nt}}^2 \times n_e^{1/2}$ ($10^{17}$ cm$^{1/2}$ s$^{-2}$) | Damping Length $D_i$ (Mm) |
|------|----------------|-------------------------|---------------------------------|--------------------------|
|      |                |                         |                                 | AR1                      |
| Fe X | 184.537        | 1.12                    |                                 | 28.31 ± 6.72             |
| Fe XI| 180.401        | 1.37                    |                                 | 46.52 ± 7.62             |
| Si X | 261.056        | 1.41                    |                                 | 114.87 ± 77.31           |
| S X  | 264.231        | 1.55                    |                                 | 65.02 ± 12.47            |
| Fe XII| 192.394       | 1.58                    |                                 | 78.49 ± 4.38             |
| Fe XIII| 202.044      | 1.78                    |                                 | 144.1 ± 12.44            |
| Fe XIV| 274.204       | 2.00                    |                                 | 75.99 ± 6.00             |
| Fe XV | 284.163        | 2.24                    |                                 | 57.68 ± 2.97             |
| Fe XVI| 262.976        | 2.82                    |                                 | 47.05 ± 2.65             |
|      |                |                         |                                 | AR2                      |
|      |                |                         |                                 | 65.19 ± 3.45             |
|      |                |                         |                                 | 52.93 ± 0.82             |
|      |                |                         |                                 | 161.69 ± 11.01           |
|      |                |                         |                                 | 56.32 ± 5.72             |
|      |                |                         |                                 | 73.70 ± 13.44            |
|      |                |                         |                                 | 118.30 ± 6.85            |
|      |                |                         |                                 | 70.06 ± 4.45             |
|      |                |                         |                                 | 57.99 ± 2.66             |
|      |                |                         |                                 | 53.85 ± 2.90             |
|      |                |                         |                                 | QS                       |
|      |                |                         |                                 | 27.54 ± 2.39             |
|      |                |                         |                                 | 33.29 ± 2.44             |
|      |                |                         |                                 | 169.95 ± 181.20          |
|      |                |                         |                                 | 84.47 ± 23.77            |
|      |                |                         |                                 | 91.95 ± 20.12            |
|      |                |                         |                                 | 159.98 ± 10.49           |
|      |                |                         |                                 | 29.31 ± 3.50             |
|      |                |                         |                                 | 26.59 ± 2.79             |
5. Summary and Conclusions

We investigated the off-limb active- and quiet-Sun regions using spectroscopic data from EIS/Hinode. We studied the height dependence of basic plasma parameters such as intensity, electron number density, and nonthermal velocity along the active region and quiet Sun. These estimated parameters enabled us to further study the height dependence of the Alfvén wave energy flux in both regions. The main findings of our analysis are summarized as follows:

1. We identified several isolated spectral lines with good signal-to-noise ratio in the off-limb regions. These lines are formed at different temperatures and cover the temperature range of 1.1–2.8 MK.

2. We obtained the electron densities and corresponding scale heights from different spectral line pairs, which suggested that the observed active- and quiet-Sun regions are basically underdense with a few exceptions measured from the quiet-Sun region.

3. Nonthermal velocities measured from warm spectral lines first showed an increase with height and later showed either a decrease or almost constant value with height in the far off-limb active region, whereas hot lines showed a gradual decrease with height. However, those measured from various spectral lines in the quiet-Sun region showed either a gradual decrease or almost constant value with height.

4. The calculated Alfvén wave energy fluxes were similar to or slightly less than the energy required to maintain the active-region corona. The results also showed damping of Alfvén wave energy flux with height.

5. We found the damping lengths of the Alfvén wave energy flux \( D_t \) to be in the range of 25–170 Mm as measured from different spectral lines formed at different temperatures.

6. The variation of the damping lengths first showed an increase and later a decrease with increasing temperature. The damping length peaked at a temperature of around 1.78 MK in both the active- and quiet-Sun regions.

This work provides measurements of nonthermal velocities and Alfvén wave energy fluxes at a wide range of temperatures. A possible interpretation of these results would either be temperature-dependent damping of Alfvén waves or measurements along different coronal structures formed at different temperatures. Possible temperature-dependent damping may suggest some important role of thermal conduction in the damping of Alfvén waves in the lower corona. This may even suggest some nonlinear coupling between Alfvén and slow MHD modes (see Zaqarashvili et al. 2006). We believe this to be an important result as this will provide more insight into the dissipation mechanism of Alfvén waves. Recent 3D MHD models of Van Ballegooijen et al. (2011) explained the role of Alfvén wave turbulence in the heating of the solar chromosphere and corona. They predicted the velocity amplitude of Alfvén waves in the corona to be in the range of 20–40 km s\(^{-1}\) so as to maintain the typical active-region loops. In our analysis, we found almost similar wave velocity amplitude in the active region. The observed damping rate of the Alfvén wave energy flux with height is similar to or slightly less than the requirements of the coronal active region. Asgari-Targhi et al. (2014) also measured nonthermal velocities in the range of 25–45 km s\(^{-1}\) using observation from EIS/Hinode along the
on-disk individual coronal loop length. Their findings were consistent with the predictions from the Alfvén wave turbulence model. However, we would also like to point out that the model of Van Ballegooijen et al. (2011) still does not include effects of thermal conduction and radiative losses. Therefore, at present, the exact form of any relation between damping length of Alfvén wave turbulence and temperature cannot be comprehended. Henceforth, these results demand the development of more sophisticated 3D MHD models of Alfvén wave propagation and dissipation including the effects of thermal conduction and nonlinear coupling between various MHD modes in the solar atmosphere.

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