Velocity Difference of Ions and Neutrals in Solar Prominences

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Abstract

Marked velocity excesses of ions relative to neutrals are obtained from two time series of the neighboring emission lines He I 5015 Å and Fe II 5018 Å in a quiescent prominence. Their Doppler shifts show time variations of quasi-periodic character where the ions are faster than the neutrals, 1.0 ≤ Vmacro(Fe II)/Vmacro(He I) ≤ 1.35 in series A and ≤1.25 in series B. This “ratio excess” confirms our earlier findings of a 1.22 ion velocity excess, but the present study shows a restriction in space and time of typically 5 Mm and 5 minutes. The ratio excess is superposed by a time- and velocity-independent “difference excess” of −0.3 ≤ Vmacro(Fe II)−Vmacro(He I) ≤ +0.7 km s⁻¹ in series A (also indicated in series B). The high repetition rate of 3.9 s enables the detection of high-frequency oscillations with several damped 22 s periods in series A. These show a ratio excess with a maximum of 1.7. We confirm the absence of a significant phase delay of He neutrals with respect to the Fe ions.

Unified Astronomy Thesaurus concepts: Solar prominences (1519)

1. Introduction

Charged particles may be faster than neutrals in a partially ionized and weakly collisional magnetized plasma (see review by Ballester et al. 2018). This ion drift can be described by a multifluid model, where the different species interact by weak coupling processes (Gilbert et al. 2002). For a detailed study of this effect, quiescent solar prominences offer a particularly good example, as they allow higher resolution in space and time than stellar objects. The observed emission of low excited lines, as Na D, shows that the prominence plasma is not fully ionized.

A velocity excess of ions over neutrals in prominences was observed and discussed in recent papers. Whereas Khomenko et al. (2016) found such an excess in restricted prominence areas with high velocities of short-lived transients, Wiehr et al. (2019) found systematically larger ion shifts through an evolutionary stable prominence. Aside from larger Doppler shifts, prominence emissions also show broader line widths for ions than for neutrals (Ramelli et al. 2012, Figure 5; Stellmacher & Wiehr 2015, Figure 1). This suggests an excess of nonthermal broadening by higher ion velocities on a very small scale.

Here, we study the excess macrovelocity of ions over neutrals in time and space from high-resolution time series. We extend and improve previous observations of the alternately measured Na I 5896 Å (D₂) and Sr II 4078 Å lines by simultaneous observations of the neighboring lines He I 5015.7 Å (singlet) and Fe II 5018.4 Å. Their small wavelength distance of 2.7 Å avoids influences by the refraction in Earth’s atmosphere, which are a relevant problem for time-series observations because the direction of refraction rotates with respect to the solar disk coordinates (see Wiehr et al. 2019).

Parasitic light, superposing the prominence emission with an absorption spectrum, shows a different rotational Doppler shift from the prominence emission lines (see Wiehr et al. 2019). This may introduce problems if a reference spectrum for the parasitic light cannot be taken in the immediate neighborhood, as for laterally extended prominences.

2. Observations

We observed a laterally small prominence at the east limb, 5° north, on 2019 June 28, from 7:45 UT through 8:25 UT (Figure 1) with the 45 cm aperture Gregory–Couéd telescope and the Czerny Turner spectrograph (f = 10 m) of the Swiss observatory Istituto Ricerche Solari Locarno. A fixed slit of correspondingly 1°5 width (1000 km on the Sun) was oriented perpendicular to the solar limb.

We took the time series of the emission lines He I 5015.7 Å and Fe II 5018.4 Å. Their brightness allowed a repetition rate of 3.9 s, which is 11 times faster than that of Wiehr et al. (2019), the spatial resolution being almost the same. Series A with 105 spectra (7:45–7:52 UT) shows smooth emissions of He and Fe II along the slit (upper part of Figure 2). Series B with 460 spectra (7:55–8:25 UT) shows brighter emissions with marked Doppler shifts and evolutionary time variations (well visible in the lower part of Figure 2). Sufficiently bright emissions of the faint lines occur in height levels of 31 Mm–50 Mm above the solar limb, the 31 Mm boundary marking the lower edge of the prominence main body seen in Hα (see Figure 1). Beyond spectrum 320 of series B (7:57 UT), this edge started to uplift with ≈9 km s⁻¹ (dashes in Figure 2), and the spectra show increasingly fragmented emissions with line satellites, announcing the “disparition brusque” at 9:45 UT.

3. Data Reduction

In order to remove parasitic light superposing the emission lines, we use spectra of the “aureola” taken immediately before and after the prominence time series at a slit position in the immediate prominence neighborhood. (For details of the reduction procedure see Ramelli et al. 2012). We average nine CCD rows, each 257 km wide (0′′35), to adapt the effective spatial resolution to the slit width.

As wavelength reference for Doppler shifts, we determine the centers of the absorption lines Ti II 5016.1, Fe I 5016.9, and Ni I 5017.5 before removing the superposed parasitic light in each individual spectrum, fitting polynomials of second degree.
This wavelength reference from the aureola is independent of complex photospheric velocity fields (e.g., oscillations and granular blueshift), which interfere if disk center spectra are used for a wavelength calibration.

We correct the velocities of each individual spectrum for the shift of the three absorption lines relative to their position in the aureola spectra. The resulting macrovelocities are thus free from spectrograph drifts and from slow terms of spectrograph seeing. The two slit positions chosen for the emission spectra and for the aureola spectra, aside from the prominence, have slightly different inclinations to the solar limb. Hence, their absorption lines show slightly different fields. That of Fe II is smaller due to the 14 times higher mass of Fe. The noise is low enough to ensure reasonable fits.

4. Results

4.1. Time Series B

Doppler time sequences of Fe II 5018.4 (full lines) and He I 5015.7 (dashed lines) are shown in Figure 4 for a four-spectra mean (15.6 s resolution) of the first 17 minutes of series B. The macroshifts give quasi-periodic velocity variations of several km s\(^{-1}\) with almost equal amplitudes for both lines. They are superposed by a velocity difference of Fe II relative to He I. This “difference excess” is nearly constant with time (i.e., spectrum number), independent of the velocity itself and diminishes at larger heights.

If we remove the time-constant ion drift, most of the differences between the Fe II and the He I velocities disappear (Figure 5), reflecting the largely equal amplitudes. However, in the time interval of minutes 4.5 through 9.5 of series B, a superposed excess of Fe II velocities becomes visible at heights \(\leq 40\) Mm above the limb. In contrast to the “difference excess,” this excess is related to the velocity itself and thus a “ratio excess”. Scatter plots (e.g., Figure 6) show that it smoothly varies with height between \(32<h<37\) Mm and disappears for \(h>40\) Mm. Its maximum amounts to \(V_{\text{macro(Fe II)}}/V_{\text{macro(He I)}} = 1.25\), in agreement with Wiehr et al. (2019).

In Figure 7 we show the time variation of the difference in the Fe II and He I velocities. (Note that the ordinate scale is about five times expanded compared to Figures 4 and 5.) The nearly constant values through the first 4.5 minutes again reflect the largely equal velocity amplitudes of Fe II and He I. We mark the shifts applied to transform Figure 4 into Figure 5 by dashed lines and vertical arrows. These vary from \(-0.35\) km s\(^{-1}\) (“blue excess”) at \(h=30.8\) Mm to \(+0.6\) km s\(^{-1}\) (“red excess”) at \(h=39.8\) Mm above the limb, yielding an almost perfectly linear gradient of 1 km s\(^{-1}\) over 11.6 Mm.

The onset of the Fe II ratio excess at spectrum-70 agrees with that in Figure 5. We thus find two species of ion drifts: (i) a velocity difference excess largely independent of the velocity itself (even though the marked velocity increase between
spectrum −40 and −70); and (ii) a ratio excess depending on velocity and restricted in space and time.

Beyond spectrum-210 (>13.5 min of recording series B), the macrovelocity of the He emission line stays increasingly behind that of the Fe ions (see Figure 4). The corresponding spectra show marked fragmentation (see Figure 2) and motions along the slit direction. Differences between Gaussian and poly fits indicate asymmetric profiles caused by the superposition of line satellites. This indicates the onset of evolutionary velocity changes announcing the sudden disappearance. We thus restrict our data analysis of series B to the first 210 spectra.

4.2. Time Series A

The spectra of series A are characterized by rather narrow and symmetric emission lines (see Figure 2). Doppler time sequences show quasi-periodic velocity perturbations with amplitudes increasing with height from 0.35 to 1.45 km s$^{-1}$ over the range of 30–44 Mm (Figure 8). Above 40 Mm, we find a velocity excess of $1.0 \lesssim \frac{V_{\text{macro(Fe II)}}}{V_{\text{macro(He I)}}} \lesssim 1.35$. At lower heights ($h \lesssim 39$ Mm), no ratio excess is observed; however, a general shift (“difference excess”) is indicated in the three lowest scan rows at $h \lesssim 36$ Mm (see Figure 8).

4.3. High-frequency Perturbations

The high repetition rate of 3.9 s enables the detection of short-period velocity variations visible in the middle scan rows of spectra 40–90 in Figure 8. To make them visible, we suppress the long-term velocity perturbations by subtracting the ten-spectra means from the two-spectra means seen in Figure 8. The resulting time series in Figure 9 shows at the height level...
An excess of 1.23.

The power spectrum in Figure 10 of the corresponding height range $38 < h < 41$ Mm over the total of 105 spectra of series A shows a pronounced peak at 46 mHz (22 s) with a significance of 99.9% for Fe II and 99.0% for He I (for details, see Balthasar 2003). Because the power maxima represent the square of the velocity amplitudes, we obtain from the square roots of the power maxima of the two emission lines their amplitude ratio. The velocity excess in the interval of 22 s oscillation amounts to 1.7. In the subinterval with pronounced oscillations (spectra 40–90), scatter plots of the He I and Fe II velocities show that the velocity excess has a spatial variation almost parallel to that of the large timescale ratio of series A (see Section 4.2).

In series B, we also find high-frequency variations with periods near 25 s in restricted intervals of space and time. These, however, show only a few cycles and thus give no significant peak in the power spectra. For the high-frequency oscillations, we do not find a significant phase shift between Fe II and He I.

5. Discussion

The observation of this prominence started $\approx$100 minutes before its sudden disappearance. It shows two species of ion excess: (i) a velocity difference $V_{\text{macro}}$(Fe II)$-V_{\text{macro}}$(He I) and (ii) a velocity ratio $V_{\text{macro}}$(Fe II)$/V_{\text{macro}}$(He I). The marked “difference excess” found in series B increases linearly with height from $-0.3$ km s$^{-1}$ (blueshift) at 30.9 Mm height to $+0.7$ km s$^{-1}$ (redshift) at 42.6 Mm height (left panel of Figure 11). A similar effect was found in Wiehr et al. (2019), where such difference excess increased between 3.3 and 39 Mm from $+0.4$ to $+2.1$ km s$^{-1}$. (Note that the velocities refer in both papers to the photosphere below the prominence.)

If we remove the time-constant difference excess, we find in the interval minutes 4.5 through 9.5 of series B a superposed ratio excess that varies smoothly between 31 and 38 Mm with a flat maximum of $V_{\text{macro}}$(Fe II)$/V_{\text{macro}}$(He I) $\approx$ 1.25 (yellow line in Figure 11). In series A, we find a ratio excess with a maximum of 1.35 (full green line in Figure 11). Both excess values are close to that of 1.22 in Wiehr et al. (2019).

In those data, the ratio excess was observed along the complete slit length. The present data, however, show a spatial restriction of the ratio excess to 3–8 Mm height. Because our observations were observed at a single cut through the prominence from a fixed slit position, we have no information about the two-dimensional spatial distribution of the ion velocity excess. In both studies, we do not find phase shifts between the Fe II and He I velocities, in agreement with Khomenko et al. (2016) and Wiehr et al. (2019).

The pronounced high-frequency oscillations with a 22 s period show an ion velocity excess with a maximum of 1.7 in a spatial interval of about 3 Mm. These short periods occur only in the time interval of minutes 3 through 6 in series A (see Figure 9). They do not vary with height, indicating stationary waves. Short-period oscillations are rarely observed in solar prominences. Balthasar et al. (1993) find 30 s periods in a
quiescent prominence, and Locans et al. (1983) observe 43 s periods in a coronal arch system around a prominence. In contrast to the high-frequency oscillations with several 22 s periods of decreasing amplitude (i.e., damped; see Figure 9), the quasi-periodic velocity perturbations of longer timescale (see Figures 4 and 8) show only a few extrema with similar amplitudes. This quasi-periodic character is typical for most velocity time-series observations in quiescent prominences (see Wiehr 2004).

The observation of a spatial and temporal restriction of the ion excess indicates an interaction of a structured velocity field with the prominence magnetic field. An impressive view of such a complex velocity field in a prominence is seen in the Hinode observations by Berger et al. (2010). The ion velocity excess will occur only under particular conditions of such a chaotic velocity field, in accordance with the findings of Khomenko et al. (2016) of an excess only in short-lived
transients with high velocities. These authors argue that the balance between ions and neutrals "is usually lost at locations with large individual velocities or large spatial or temporal gradients," and further that they "are smoothed by interactions on relatively short timescales (typically of the order of minutes)" (Khomenko et al. 2016, page 9). The observations of the ion–neutral velocity ratio excesses described here are indeed limited in space and time.

The present observations were made ≈100 minutes before the sudden disappearance of the prominence, which may announce itself by the increasingly chaotic velocity field. In contrast, finding a systematic excess during the full observing time through the whole prominence time (Wiehr et al. 2019) was obtained from a long-living quiescent prominence. Hence, the dynamic behavior of the prominence seems to play an essential role in the detectability of an ion velocity excess over neutrals.

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