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Detection of polarization from the $E^4\Pi - A^4\Pi$ system of FeH in sunspot spectra

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ABSTRACT

Here we report the first detection of polarization signals induced by the Zeeman effect in spectral lines of the $E^4\Pi - A^4\Pi$ system of FeH located around 1.6 μm. Motivated by the tentative detection of this band in the intensity spectrum of late-type dwarfs, we have investigated the full Stokes sunspot spectrum finding circular and linear polarization signatures that we associate with the FeH lines of the $E^4\Pi - A^4\Pi$ band system. We investigate the Zeeman effect in these molecular transitions pointing out that in Hund's case (a) coupling the effective Landé factors are never negative. For this reason, the fact that our spectropolarimetric observations indicate that the Landé factors of pairs of FeH lines have opposite signs, prompt us to conclude that the $E^4\Pi - A^4\Pi$ system must be in intermediate angular momentum coupling between Hund's cases (a) and (b). We emphasize that theoretical and/or laboratory investigations of this molecular system are urgently needed for exploiting its promising diagnostic capabilities.

Subject headings: magnetic fields — molecular data — polarization — Sun: magnetic fields

1. Introduction

FeH constitutes one of the most important opacity contributors in late-type dwarfs, in the red and near-infrared between 0.7 μm and 1.3 μm. It was however detected in the atmospheres of late M dwarfs much later than many of the other hydrides formed with less abundant atomic species. This is probably due to the fact that the FeH spectrum is very complicated, arising from quartet and sextet terms (Langhoff & Bauschlicher 1990).

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Although some bands are in the optical and blue part of the spectrum, the crowding of atomic lines makes it difficult to distinguish FeH bands. For this reason, the most studied FeH electronic system is that produced by the transition $F^4\Delta - X^4\Delta$. This band system, widely used in studies of late-type dwarfs, produces a conspicuous absorption near 1 μm. A theoretical analysis of this band system has been performed by Phillips et al (1987) with the assignation of quantum numbers to many of the observed lines of the $v = 0 - 0$ band.

In a recent study of the infrared intensity spectrum of sunspots, Wallace & Hinkle (2001) identified almost 70 lines between 1.58 μm and 1.755 μm common to both the sunspot spectrum and a furnace laboratory spectrum of FeH . They tentatively associated these lines to the $E^4\Pi - A^4\Pi$ system based on the theoretical work of Langhoff & Bauschlicher (1990). These authors predicted this band system to be around 2 times weaker than the $F^4\Delta - X^4\Delta$ system, even though the $E^4\Pi - A^4\Pi$ is one of the strongest bands of the quartet system in FeH. Later, Cushing et al (2003) compared the near-infrared spectrum of four late-type dwarfs with the laboratory FeH spectrum, finding 34 features that dominate in the H-band spectra. They associated some of these features to the $v = 0 - 0$ $E^4\Pi - A^4\Pi$ band of FeH. They found a very similar behavior of this band and the other IR bands of FeH when observing stars of different spectral types, thus reinforcing that these features belong to FeH.

There are almost no studies of the polarization properties of FeH lines. A first attempt has been carried out by Berdyugina et al (2001) and by Berdyugina & Solanki (2002) for lines of the $F^4\Delta - X^4\Delta$ system, assuming that the angular momentum coupling is that given by Hund's case (a) (see Herzberg 1950). These authors were forced to use Hund's case (a) coupling because no estimation of the spin-orbit coupling constants of the electronic states of the transition are available. In view of the effective Landé factors, they concluded that the $F^4\Delta - X^4\Delta$ band system of FeH might be of interest for the investigation of the magnetic properties of solar and stellar atmospheres.

In this letter, we present the first full Stokes observations of FeH in the near infrared, showing that the $E^4\Pi - A^4\Pi$ band system must be in intermediate coupling between Hund's cases (a) and (b). To our knowledge, this is the first time polarization signals in FeH are observationally detected in sunspots.

2. Observations

The observations were carried out on June 7, 2002 with the Tenerife Infrared Polarimeter (TIP; see Martínez Pillet et al 1999) mounted on the German Vacuum Tower Telescope (VTT) at the Observatorio del Teide (Spain). The observed sunspot was located out of

the solar disk center, at $\mu = 0.68$ (being μ the cosine of the heliocentric angle), so that linear polarization signals may be expected. The total size of the umbra was ∼18". The presence of a light bridge crossing the sunspot umbra led us to select only those points within the umbra whose polarization properties are not contaminated by the presence of the light bridge. Interestingly, the depth of the observed FeH intensity profiles is reduced close to the light bridge, possibly due to the dissociation of the FeH molecules caused by a temperature increase. Similarly, we also found a smaller amplitude in the Stokes V spectrum.

The spectral resolution of the observation was ∼26 mÅ with a total wavelength coverage of ∼7 Å. In order to investigate the polarization properties of FeH lines, we performed three scannings with a step of 0.4" for different spectral regions and three time series with the slit crossing the center of the umbra. The integration time for each position in the scannings was 1 second, while the total integration time for the time series was between 5 and 10 minutes. Although the detection of the FeH features is obtained also in the 1 second integrations, we have used the temporally averaged Stokes profiles because they have better signal-to-noise ratio. The typical noise level is $\sim 10^{-4}$ of the continuum intensity.

As shown below in Fig. 4, the observed FeH lines, apart from producing conspicuous antisymmetric V signals, also show perfectly detectable symmetric Stokes Q and U profiles. However, in this first paper we will only focus on Stokes V.

3. The Zeeman effect in FeH

Since no perturbation analysis has been performed for any of the electronic states of FeH, no spin-orbit coupling constants are available. This makes it necessary to treat the lines of both the $F^4\Delta - X^4\Delta$ and the $E^4\Pi - A^4\Pi$ system in any of the limiting Hund's coupling cases. However, according to Berdyugina & Solanki (2002), the $F^4\Delta - X^4\Delta$ system is known to be in intermediate coupling between (a) and (b) and strong deviations of the effective Landé factor $\bar{g}$ for the lines of the P and R branches are expected from that given by Hund's case (a). In particular, $\bar{g}$ for the lines of the P and R branches will increase as J increases. This increase in the Zeeman sensitivity has been observed by Wallace et al (1999) in the intensity spectrum of sunspots associated to an increase in the broadening of the high J lines. A similar behavior is expected for the lines of the $E^4\Pi - A^4\Pi$ band. Wallace & Hinkle (2001) apparently detected such a behavior from the line splitting in the intensity spectrum. They found many FeH lines which appear undoubled but a set of seven lines around 15930 Å which present a splitting, probably caused by the Zeeman effect since it increases with the field strength in sunspots.

For those electronic levels with $\Lambda \neq 0$, the spin-orbit coupling constants are usually large (see Huber & Herzberg 2003). Therefore, the energy separation associated to the multiplet splitting is expected to be large. We also expect the spin-orbit coupling to be large enough so that the field at which the transition to the Paschen-Back regime occurs is larger than the typical field strength of sunspots. In fact, this is the case with all the molecules studied by Berdyugina & Solanki (2002) presenting $\Lambda \neq 0$. If the FeH lines that belong to the $E^4\Pi - A^4\Pi$ system are indeed in the Zeeman regime, we expect Stokes profiles similar to those of a normal Zeeman triplet. This is in fact confirmed by the observations.

The effective Landé factors calculated in Hund's case (a) coupling for the Q branch lines of the $E^4\Pi - A^4\Pi$ band are shown in Fig. 1. The effective Landé factor ($\bar{g}$) can be obtained easily from Herzberg's (1950) formulae for the Landé factors of the lower and upper levels. Since such Q-branch lines result from transitions between electronic levels with the same quantum numbers, $\bar{g}$ can be written simply as

$$\bar{g} = \frac{(\Lambda + 2\Sigma)(\Lambda + \Sigma)}{J(J+1)}, \tag{1}$$

where $\Lambda = 1$ and $\Sigma = 3/2, 1/2, -1/2, -3/2$. We point out that $\bar{g} = 0$ for the lines of the P and R branches and that the lines between levels with $\Lambda + \Sigma = 1/2$ are insensitive to the magnetic field. The rest of the spectral lines belonging to transitions between low J levels seem to be as sensitive to the magnetic field as those of the $F^4\Delta - X^4\Delta$ system studied by Berdyugina & Solanki (2002). It is very important to note that all the values of $\bar{g}$ are non-negative, contrary to what happens for the $F^4\Delta - X^4\Delta$ system. We also show in Fig. 1 the effective Landé factor obtained for the lines of the main Q branch using Hund's case (b) coupling. Note that in this coupling case $\bar{g}$ can take positive and negative values. The same is valid for the lines of the P and R branches.

Although little magnetic field diagnostics can be presently done with these lines given the lack of precise spectroscopic data, we have used the observed polarization signals in order to obtain a first insight into the potential diagnostic interest of these FeH lines.

4. Discussion

We have observed three spectral regions. A region around 16605 Å, another one around 16110 Å, and a third one around 16575 Å. The observation of the first region was motivated by the presence of two vibration-rotation OH lines of the $X^2\Pi$ level, similar to those observed by Harvey (1985). Because the spectroscopic constants of OH are known, these lines can be used to obtain information about the magnetic field in sunspots. To this end, as shown in

Fig. 2, we have performed LTE syntheses in the hot umbra model of Collados et al (1994) finding that a constant vertical magnetic field of 1800 G pointing radially outwards leads to a fairly good fit to the observed Stokes profiles in the OH lines[2]. The Zeeman patterns for the OH lines have been obtained applying the theory developed by Schadee (1978), thus they do not depend on any assumption about the coupling. We point out that since the OH lines are stronger than the FeH lines, a magnetic strength of 1800 G gives only a lower limit to the strength of the field in the deeper regions of the sunspot umbra where the FeH polarization is originated. Assuming a typical gradient of 5 G km^{-1} (Collados et al 1994), we estimate that the magnetic field in the formation region of the FeH lines may be about 600 G higher than in the OH formation region. For this reason, we have assumed B≈2400 G in the following estimations of the effective Landé factors of the observed FeH lines.

In order to obtain information about the approximate value of the effective Landé factor of the FeH lines, we have applied two different techniques. The first one assumes that the line is formed under the weak field (WF) approximation (e.g. Landi Degl'Innocenti 1992). Molecular lines usually have small effective Landé factors except for lines that arise between levels with very small values of J (see Herzberg 1950; Landau & Lifshitz 1982). Since the Zeeman splitting in the IR is relatively large, and assuming typical thermal and microturbulent velocities, the weak field approximation is valid for $\bar{g}B \ll 1000$ G, which is somewhat restrictive for some of our FeH lines. The second technique assumes that the line is formed in the strong field (SF) regime so that peak separation in Stokes V is indicative of the separation of the σ components when they are fully split. Since the lines are not in any of these limiting regimes, the correct effective Landé factors will be between the values obtained via the two techniques (assuming that our estimation of the sunspot magnetic field strength is sufficiently afortunate).

Fig. 3 shows two FeH lines at 16108 Å, one of which produces a clear circular polarization signal, while the other is apparently insensitive to the Zeeman effect. We show in the same figure the fit obtained to the line at 16108.3 Å by plotting the derivative of the intensity spectrum multiplied by the scaling factor using $\bar{g}_{\rm WF} = 0.09$, which represents an approximation to the effective Landé factor of this line. Note that the fit of the magnetic sensitive line is strikingly good for this combination of field strength and $\bar{g}$. From the previous fit, we can infer that the strong field regime has not been reached, since the separation of both Stokes V lobes are correctly obtained with the weak field formula. This is reinforced by the low value obtained for $\bar{g}$. In the strong field regime, we obtain $\bar{g}_{\rm SF} \approx 0.24$.

[2]The LTE synthesis in the cool umbra model of Collados et al (1994) presents OH line absorptions much deeper than the observations.

The FeH line at 16107.8 Å may be assumed to have $\bar{g} \approx 0$, in principle, since at first sight there seems to be no significant signal in Fig. 3. However, a closer inspection indicates that a very small V signal with $\bar{g} < 0$ seems to be present in our observations. This may constitute a first indication that deviations from Hund's case (a) are expected for these lines. Another but much stronger indication will be discussed below.

Fig. 4 shows three FeH lines around 16575 Å which have been detected previously in intensity by Wallace & Hinkle (2001). These lines are quite weak in the sunspot intensity spectrum and it has been a bit difficult to apply the weak-field approximation since the derivative of the intensity profile turns out to be very noisy. We have obtained $\bar{g}_{\rm WF} \approx 0.38$ for the line at 16571.5 Å and $\bar{g}_{\rm WF} \approx -0.38$ for the line at 16576.8 Å. According to the results shown in Fig. 1, a negative $\bar{g}$ is not possible in Hund's case (a) coupling. This constitutes our strongest proof that this band of FeH is in the intermediate coupling case between Hund's cases (a) and (b). The coupling constants and the line identifications have to be obtained in case the lines of this band are to be used as tools for diagnosing magnetic properties of the coolest regions of sunspot atmospheres or magnetic fields on cool dwarfs. The line at 16575 Å seems to be a blend of some FeH lines at slightly different wavelengths due to the intricate structure of Stokes V with apparent cancellations among them. The linear polarization signal is shown in the lower panel of Fig. 4. Note that all the FeH lines produce conspicuous Stokes Q and U features with an amplitude of around 1%. If we assume that the lines are in the strong field regime, we obtain $\bar{g}_{\rm SF} \approx 0.39$ for the line at 16571.5 Å and $\bar{g}_{\rm SF} \approx -0.28$ for the line at 16576.8 Å from the peak separation in Stokes V.

Our previous results can be compared with the effective Landé factor obtained from the fully split FeH lines in the atlas of the umbral spectrum of Wallace & Livingston (1992). For a field of 3500 G obtained from the fully split V I line at 16570.5 Å whose effective Landé factor is $\bar{g} = 0.7$, one obtains $\bar{g}_{\rm SF} \approx 0.27$ and $\bar{g}_{\rm SF} \approx -0.19$ for the lines at 16571.5 and 16576.8 Å respectively. Comparing with the results obtained directly from our spectropolarimetric observations, we verify that in the sunspot we observed we are in the intermediate field regime.

5. Conclusions

We have shown observational evidence that the lines of the $E^4\Pi - A^4\Pi$ electronic system of FeH present circular and linear polarization signals that are produced by the Zeeman effect. We have estimated the magnetic field strength with the help of two OH lines and inferred the effective Landé factors of the FeH transitions using either the weak-field or the strong-field approximations. We have shown that the $E^4\Pi - A^4\Pi$ band of FeH presents lines

with negative effective Landé factors, which is impossible under Hund's case (a) coupling. Therefore, we conclude that this molecular band system must be in intermediate angular momentum coupling between Hund's cases (a) and (b). The FeH lines studied here are potentially interesting for empirical investigations of the physical conditions in the lower atmosphere of sunspots and of the magnetism of late-type dwarfs. To this end, theoretical and/or laboratory investigations of this FeH molecular system are urgently needed.

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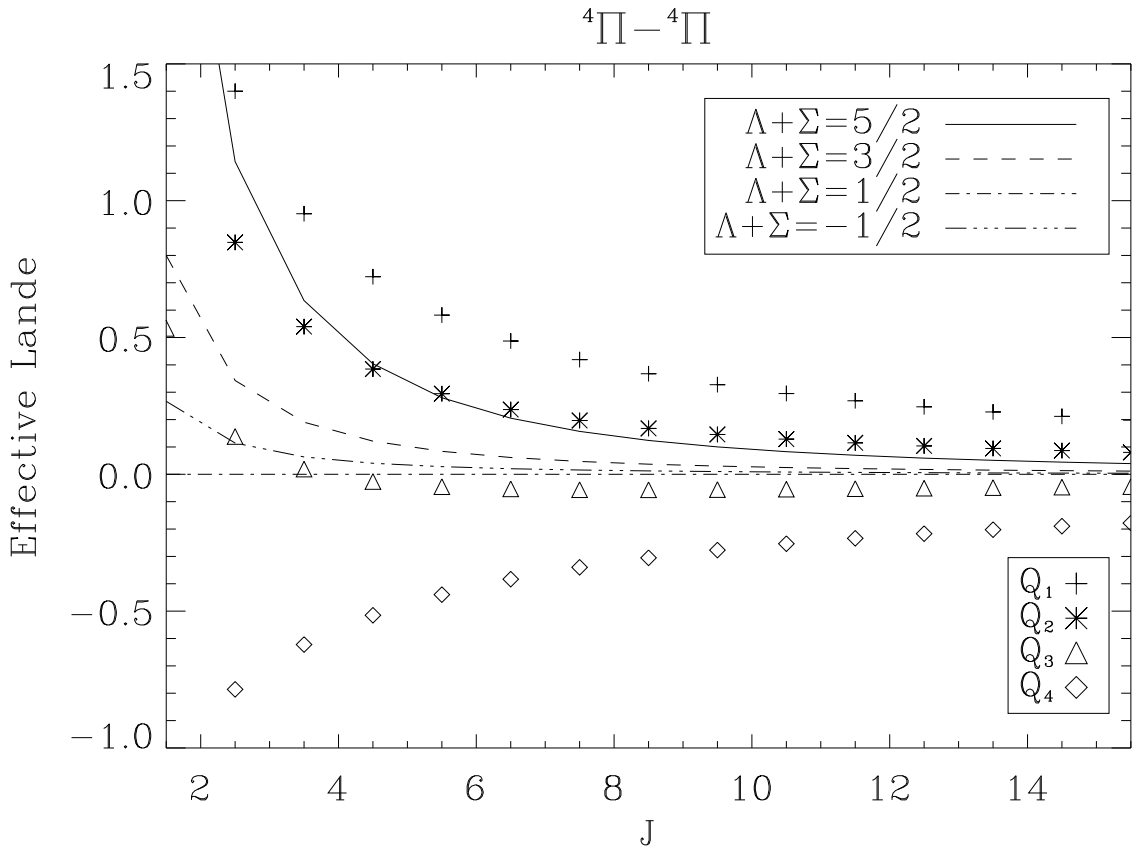


Fig. 1.— Effective Landé factor of the Q branch of the $E^4\Pi - A^4\Pi$ band system of FeH calculated using Hund's case (a) coupling (lines) and Hund's case (b) coupling (symbols). The lines between the $\Lambda + \Sigma = 1/2$ levels are completely insensitive to the magnetic field in Hund's coupling case (a). Note that while the effective Lande factor is always non-negative for Hund's case (a) coupling, it can become negative for Hund's case (b) coupling.

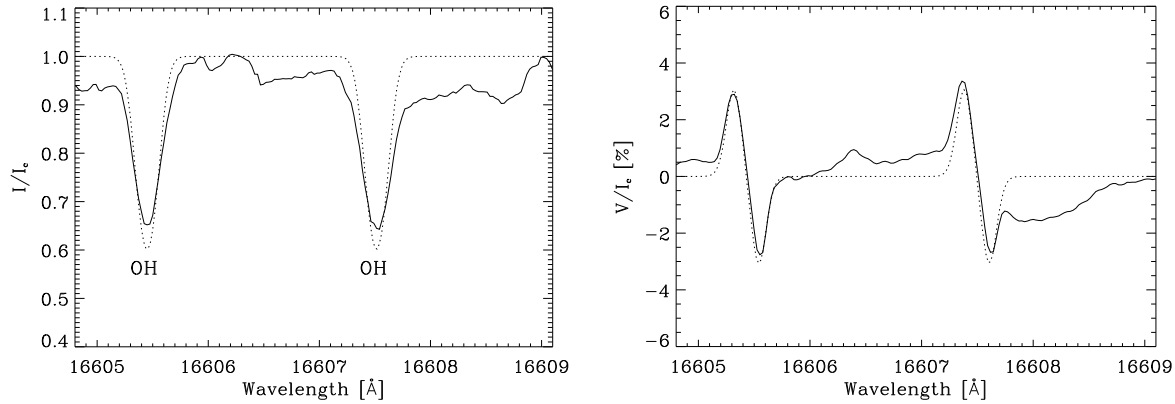


Fig. 2.— Two OH lines close to the studied FeH lines. Since the coupling constants of OH are known, we have calculated the emergent Stokes profiles from the Collados et al (1994) hot umbra model, finding that a constant magnetic field of 1800 G provides a fairly good fit the observed Stokes profiles. The solid line represents the observation while the dotted line is the modeling.

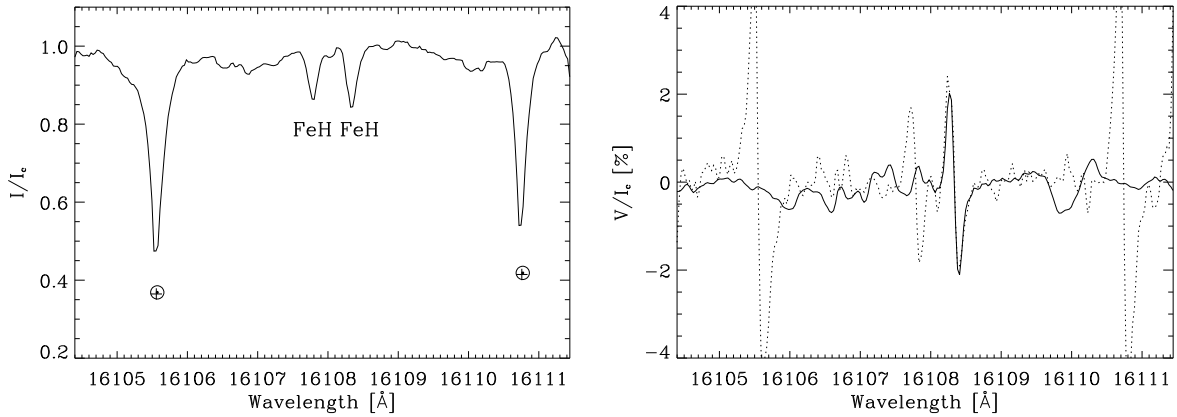


Fig. 3.— Observed FeH lines together with the fit obtained via the weak-field approximation for B =2400 G. The two strong lines in the extremes of the spectral interval are telluric absorption produced by CH_4. The solid line represents the observation while the dotted line the derivative of the intensity spectrum scaled with $\bar{g} = 0.09$ in order to fit the line at 16108.3 Å.

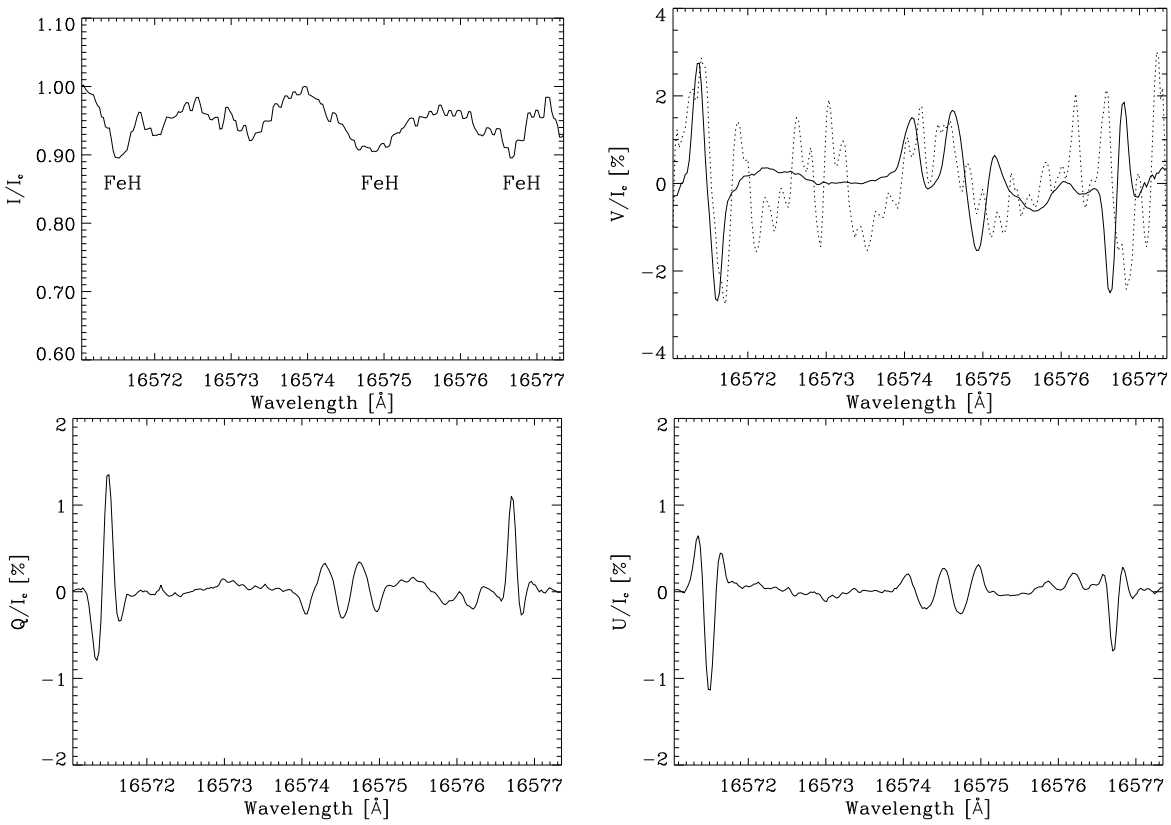


Fig. 4.— Region with several FeH lines producing weak absorptions in the intensity spectrum but very clear features in the circular polarization spectrum. We show also the derivative of the intensity spectrum scaled with $\bar{g} = 0.38$. Note that the line near 16577 Å has negative effective Landé factor. The two lower panels show the observed linear polarization spectrum.