Study of photospheric line depth variations along the solar cycle

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Abstract. We study the behaviour of three photospheric lines (Fe I 537.9, C I 538.0 and Ti II 538.1 nm), monitored on the Sun since 1978, either as full-disk or as center-disk measurements. The aim is to detect photospheric variations with the cycle. We reconstruct the cyclic variations of full-disk line depths as due to the active region modulation, through a spectral synthesis with FAL semiempirical models (Fontenla et al.). We show that ARs alone cannot account all the observational results. The difference between observed behaviour of these three lines at full-disk and the AR contribution as predicted by the models, correlates with the measured center-disk line variations, and a common periodicity of ~ 2.8 yr is present.

Key words. Sun: line formation - Sun: activity - Sun: faculae, plages

1. Introduction

The total solar irradiance (TSI) varies ~ 0.10% in phase with magnetic activity (Fröhlich 2003). Superposed on 11 yr trend, there are variations on shorter times scales (hours and days) that are wholly due to the active regions (ARs). ARs are the cause of a large part of variations over magnetic cycle times (Krivova et al. 2003), but the existence of a background variation is still debated (Lydon et al. 1996). In other word, in the literature there are two views: the first one ascribes all the irradiance variations to the evolution of the surface magnetic fields and that these features are superposed to an otherwise constant background; the second one says that the solar global structure may change as a consequence of variations of the magnetic field both in the solar interior, where activity modifies the boundary condition.

Moreover there are indications (Akioka et al. 1987) of a fine structure in solar cycle, in particular of a quasi-biennial oscillation (QBO). QBOs are found in many geophysical processes (Baldwin et al. 2001).

The study of photospheric lines can represent a method to detect global changes not directly linked to active region presence, even if their sensitivity to different parameters and to AR presence have to be taken into account (Caccin et al. 2002; Penza et al. 2004b).

Since 1978 the line depths of three photospheric lines (Fe I 537.95, C I 538.03 and Ti II 538.10 nm) have been measured, both full-disk
1997 we report the recon-
Krivova et al.
Tritschler and
Penza et al. (2)
shows that, at first order, the di-
2003
2004a
2004b
2003
2004
2004b
2003
(1)
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Walton et al. Fontenla et al.
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2004b
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(2)
We study the line variations as due to AR mod-
quiet sun). The sensitivity of the Fe I, C I and Ti II
 tors) of
(1978-1985), while in the period where the di-
struction of the thre line depth variations, us-
storation is valid for line behavior.
(Gray and Livingston [1997] FD) and at center-
disk (Livingston and Wallace [2003] CD). The
characteristics of these lines, their response to
the temperature changes and the AR effects
on them, have been analyzed in a previ-
paper (Penza et al. [2004b]).
In this work we try to account for line cyclic
behaviour by implementing a simplified model
in order to reconstruct line depth trends along
the cycle. We estimate how much of the varia-
tions measured at full disk can be attributed to
AR modulation and show that a part of it must
be derived from other phenomena.
We stress the existence of a shared periodicity
(for all the lines and for other activity indica-
tors) of ~ 2.8 yr.

2. Reconstruction of the line
variations

The sensitivity of the Fe I, C I and Ti II
lines to the ARs was analyzed in Penza et al.
(2004b), where the line depths were computed
for Fontenla models (Fontenla et al. [1999]),
representing quiet sun, network and faculae. We
reproduce the trend of the line depths (in-
tegrated over the disk) by weighting dif-
cent models with corresponding coverage
factors, in analogy with TSI reconstruction in
the literature (Penza et al. [2003] Krivova et al.
2003) e.g.). This is given by:

\[ D = \frac{\sum_j \alpha_j I_j^f D_j}{\sum_j \alpha_j I_j^c}, \]

where \( \alpha_j \) is the coverage factor of the j-th struc-
ture (quiet sun, network, facula or spot), \( I_j^f \) is
the corresponding intensity at the line center
and \( I_j^c \) the continuum.

Through simple algebraic passages, we obtain
that the first order variation of \( D \) results:

\[ \frac{\delta D}{D} \approx \frac{\delta D_q}{D_q} + \sum_{j \neq q} \alpha_j \frac{\delta I_j^f}{I_j^c}(d_j - 1) + \sum_{j \neq q} \alpha_j \frac{\delta I_j^c}{I_j^c}(d_j - 1), \]

where \( \delta I_j^f = I_j^{f^q} - I_j^q \) and \( d_j = D_j^{f^q}/D_q \) (q =
quiet sun).

We study the line variations as due to AR mod-
ulation alone, so we consider in Eq. 2 only the
second term.

We use the coverage factors provided by
Chapman and Walton (private communi-
cation, for more details see e.g. Walton et al.
(2003a,b), for the 1986-2002 period and the
Mg II index as proxy of the coverages during
the 1978-1985 period.

We use modE and modF as representative of
network and facula models, because they are
the models reproducing center-limb contrast of
the structures (Penza et al. 2004a) and the line
depth contrast between facular zones and the
quiet sun (Penza et al. 2004b). Instead we use a
mean contrast for the average spot (umbra plus
penumbral) as equal 0.56. This estimation is de-
derived by weighting the contrast corresponding
to umbra and penumbra \((F_{um}/F_q = 0.35 \text{ and}
F_{pen}/F_q = 0.76)\), suggested by Tritschler and
Schmidt (2002) with their coverage ratio.

The comparison between the reconstruction
via models and the observed data from
VIRGO/SOHO satellite (Frohlich 2003), (ver-
sion 5-007-0310a) is shown in Fig. 1. The av-
average TSI variations are well reproduced in the
period where we have used the coverage fac-
tors obtained by calibration with the Mg index
(1978-1985), while in the period where the di-
rect estimate of the values of faculae and spots
area (1986-2003) are used, we are able to re-
produce also the variations on shorter time-
scales.

We should then expect that an analogous
reconstruction is valid for line behavior. Unfor-
fortunately, that is not the case. If we try to re-
construct the trend of the line depths along
the cycle the result does not match very well
with the observed data.

In the left panel of Fig. 2 we report the re-
construction of the three line depth variations,
using the same models of the TSI reconstruc-
tion. It is evident that there are problems both
with respect to the variation in amplitude an to
the phase.

In other words, if the observations are correct,
another competitive effect needs to be taken into
account.

Eq. 2 shows that, at first order, the differences
between the overall variations and those due to
ARs should give an estimate of the FD back-
ground variations. Then, as a first (and rough)
Fig. 1. Comparison between the observed TSI from VIRGO/SOHO (grey points) and the reconstruction obtained through models and spectral synthesis (black points).

comparison, we can compare the difference between FD variations (observational data) and the modulation due solely to ARs (semiempirical reconstruction) with the observational data corresponding to variations of line depth at the CD (right panel of Fig. 2). Actually, the two series of the values are not really comparable, because the FD data could be affected also by a possible limb-darkening variation of the continuum and/or of the line depths. Moreover, the CD data are averaged over the granulation structure, which might change (Roudier 2003). Nevertheless, we suggest that also these possible effects would have the same origin, i.e. the same periodicity. Fig. 2 shows just two trends that are similar in periodicity, even if less in amplitude.

### 3. Periodicity analysis

We study the periodicities of the observational data. In particular we use the Lomb (1976) and Scargle (1982) formalism, that provides the power spectra of unevenly sampled data as a function of angular frequency $\omega = 2\pi f$.

<table>
<thead>
<tr>
<th></th>
<th>FD</th>
<th></th>
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<th>CD</th>
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<tbody>
<tr>
<td>Fe</td>
<td>9.5</td>
<td>8.6</td>
<td>8.50</td>
<td>10.5</td>
<td>-</td>
<td>10.5</td>
</tr>
<tr>
<td>C</td>
<td>2.78</td>
<td>2.9</td>
<td>2.90</td>
<td>2.76</td>
<td>2.9</td>
<td>2.8</td>
</tr>
<tr>
<td>Ti</td>
<td>-</td>
<td>1.33</td>
<td>1.39</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Fe</td>
<td>-</td>
<td>1.01</td>
<td>1.02</td>
<td>1.01</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>C</td>
<td>-</td>
<td>-</td>
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<tr>
<td>Ti</td>
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Table 1. Line periodicities (in yr) obtained by power spectra of the two line data series (FD and CD).

In order to avoid problems due to the biggest temporal gap, we analyze only the period where the data are, more or less, uninterrupted, i.e. from 1978 to 1992.

The power spectra relating ti FD and CD data are shown in Fig. 3. The periodicities having a confidence greater than 99% are reported in Table 3. Here we do not report the periodicities less than 1 yr, but we may remark that all the data contain a solar rotation signal from 0.07 to 9.985 yr.

We consider separately the two data series: the
three lines at FD share an unique periodicity (about 2.8 yr), and also a periodicity near to the cycle, 9.5 yr and 8.5-8.6 yr for Fe line and for the C and Ti lines, respectively. The periodicity near to 1 yr for the FD dara are ascribe to the earth’s orbit, i.e. to variation of the magnetic structure size projected on the grating over the solar surface owing to elliptic
The middle term, at about 1.3-1.4 yr is present only for C and Ti, but actually a peak is present also in Fe power, even though at a lower power (corresponding to a confidence of about 95%). The results for the CD data are less numerous and more clear: the only periodicity of 2.8-2.9 yr is shared by all the lines, while a periodicity of 10.5 yr (due of course to the magnetic cycle) is present only in Fe and Ti. Altogether, the lines seem to feel the effect of the magnetic cycle, even if with different temporal response each from other, but are simultaneously affected by some other phenomenon, with period ~ 2.8 yr. That could be a signal of a background contribution, which is, in principle, no strictly linked to magnetic activity.

In order to verify that the periodicities at 2.8-2.9 yr are not mathematical harmonic of the higher period (e.g. the 11-year cycle) we have repeated the analysis by splitting the sample, i.e. excluding the longest periodicities. The result is a substantial peak, slightly shifted forward to near 3 yr.

We repeat the temporal analysis for some available solar data, such as TSI, facular and spot coverages, green (Fe XIV 530.0 nm) coronal emission line (http://www.ngdc.noaa.gov/stp/SOLAR). In Table 2 we report the most important periodicities for each index, neglecting those shorter than 1 yr. The temporal analysis shows that the periodicity around 2-3 yr is present in all the activity indexes.

| Facula Spot Fe XIV TSI (ACRIM) | 10.8yr 10.4yr 9.5yr 10.4yr |
|-------------------------------|-------------------|-----------------|-----------------|
| Facula Spot Fe XIV TSI (ACRIM) | 5.45yr 5.55yr - 5.45yr |
| Facula Spot Fe XIV TSI (ACRIM) | - 4.13yr 4.68yr 3.83yr |
| Facula Spot Fe XIV TSI (ACRIM) | 3.25yr 3.20yr 3.25yr 3.24yr |
| Facula Spot Fe XIV TSI (ACRIM) | 2.7yr 2.7yr 2.4yr 2.6 - 2.86yr |
| Facula Spot Fe XIV TSI (ACRIM) | 2.17yr 2.2yr - 2.15yr |
| Facula Spot Fe XIV TSI (ACRIM) | 1.8yr 1.8yr 1.76yr 1.8yr |

Table 2. Periodicities (in yr) of activity indexes analyzed via Lomb-Scargle periodogram.

4. Discussion and Conclusions

We have tried to reconstruct the variations of line depths of three photospheric lines that were monitored for more than twenty years,
both in full and at center disk. We have considered two possible contributions to their variations. The first one is a magnetic contribution, arising from the sensitivity of the lines to the active regions, and to their coverage variations along the cycle. We find that the principal contribution of this magnetic part comes from faculae, while the effect of spots and network is neglectable. By considering alone the variations of the active regions we are able to reproduce the TSI variations from 1978 to 2004, but not all the variation of the lines. In particular, neither the amplitude nor the phase seem well reproduced by AR contributions alone. This second effect has been denoted as a "non-magnetic contribution", where this appellation can contain any effect not strictly linked to faculae, spots and network. The difference between the observational line variations at full disk with the evaluated AR contribution has been compared with the observational line variations at center disk (theoretically not affected by AR presence). The two data series seem very similar. The periodicity analysis (that takes into account the uneven sampling of the data) highlights the existence of a quasi-biennial modulation (about 2.8 yr), shared by all the lines, both at full and at center disk, and by other activity indicators, such as faculae and spot areas and the coronal index and TSI. The capability of reconstructing the TSI variations by imposing the AR area variations alone (and the impossibility to do the same thing with the line depths) is probably due to the lesser sensitivity of the total irradiance to several changes with respect to the line depths. For example, we known that it is possible to have the same total flux by synthesizing one dimensional atmospheric models having different parameters; in fact the flux depends on $T_{\text{eff}}$ alone, while a line depth can depend on the gravity, on the abundance, and on the value of microturbulence.

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