Mem. S.A.It. Vol. 76, 856

Memorie della

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 contributionm 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

(Gray and Livingston 1997, FD) and at center-disk (Livingston and Wallace 2003, CD)). The characteristics of these lines, their response tothe temperature changes and the AR effects on them, have been analyzed in a previous 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 variations 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 indicators) 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 (integrated over the disk) by weighting different model results 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:

$$D = \frac{\sum_j \alpha_j I_c^j D_j}{\sum_j \alpha_j I_c^j}, \quad (1)$$

where α_j is the coverage factor of the j-th structure (quiet sun, network, facula or spot), I_λ^j is the corresponding intensity at the line center and I_c^j the continuum.

Through simple algebraic passeges, we obtain that the first order variation of D results:

$$\frac{\delta D}{D} \cong \frac{\delta D_q}{D_q} + \frac{\sum_{j\neq q} \delta\alpha_j i_c^j (d_j - 1)}{\sum_{j\neq q} \alpha_j i_c^j (d_j - 1) + 1}, \quad (2)$$

where $i_c^j = I_c^{j\neq q}/I_c^q$ and $d_j = D_{j\neq q}/D_q$ (q = quiet sun).

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

We use the coverage factors provided by Chapman and Walton (private communication, 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 rapresentative 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 penumbra) as equal 0.56. This estimation is derived by weighting the contrast corresponding to umbra and penumbra ($F_{um}/F_q = 0.35$ and $F_{pen}/F_q = 0.76$), suggested by Tritshler and Schmidt (2002) with their coverage ratio.

The comparison between the reconstruction via models and the observed data from VIRGO/SOHO satellite (Fröhlich 2003), (version 5-007-0310a) is shown in Fig. 1. The average TSI variations are well reproduced in the period where we have used the coverage factors obtained by calibration with the Mg index (1978-1985), while in the period where the direct estimate of the values of faculae and spots area (1986-2003) are used, we are able to reproduce also the variations on shorter timescales.

We should then expect that an analogous reconstruction is valid for line behavior. Unfortunately, that is not the case. If we try to reconstruct 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 reconstruction of the three line depth variations, using the same models of the TSI reconstruction. 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 background variations. Then, as a first (and rough)

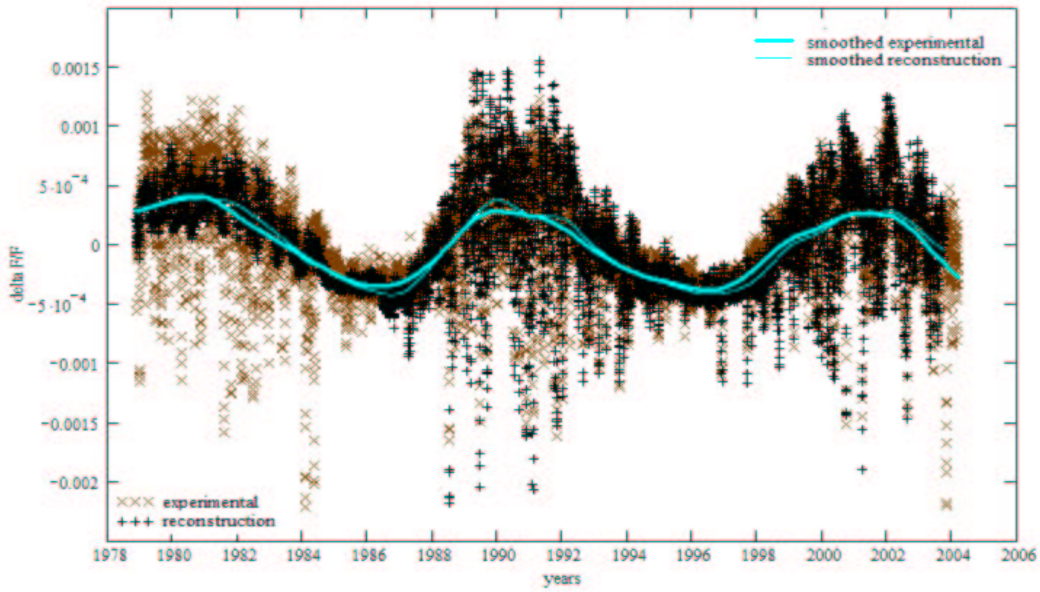

Fig. 1. Comparison between the observed TSI from VIRGO/SOHO (grey points) and the reconstruction obtained through models and spectral synthesis (black points).

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 $\omega = 2\pi f$.

FD			CD		
Fe	C	Ti	Fe	C	Ti
9.5	8.6	8.50	10.5	-	10.5
2.78	2.9	2.90	2.76	2.9	2.8
-	1.33	1.39	-	-	-
1.01	1.02	1.01	-	-	-

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

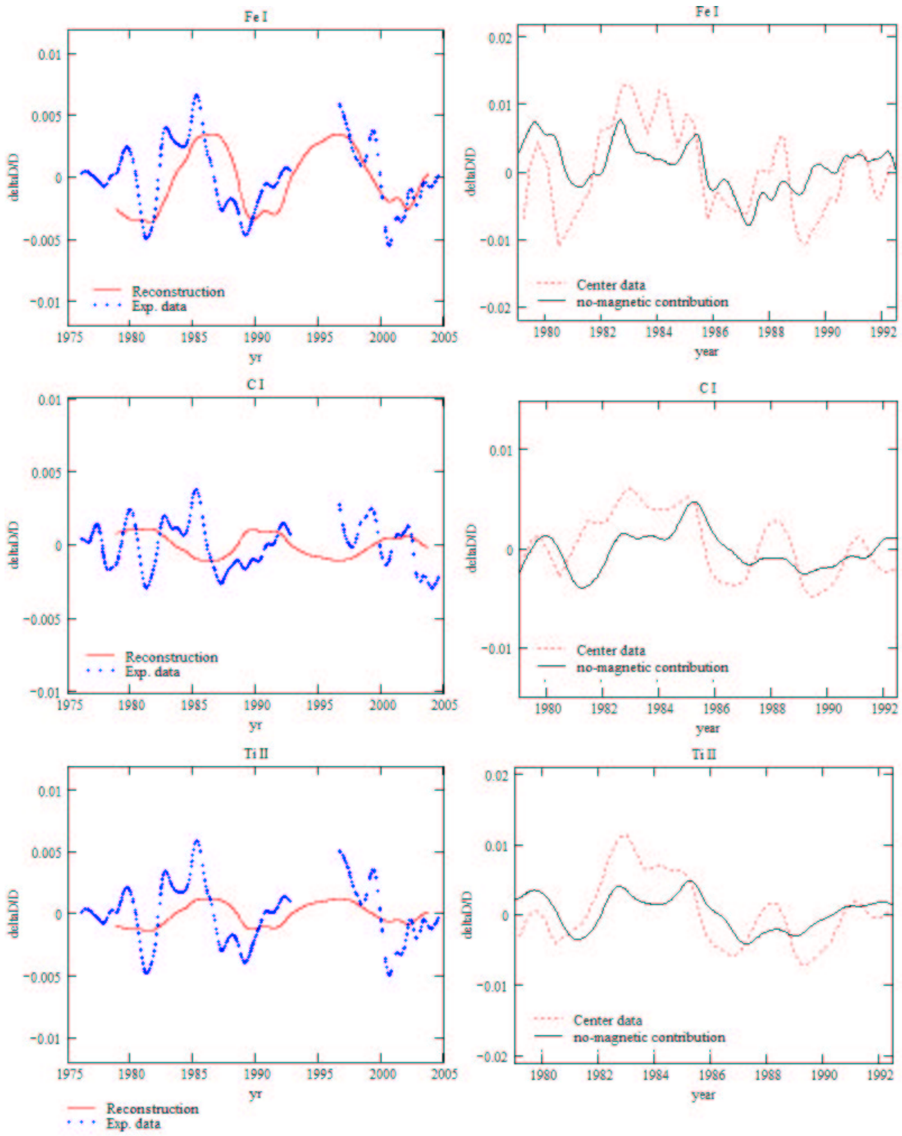

Fig. 2. Left panel: reconstruction of the line variations due to alone ARs (solid line), compared with the observational daily FD data by Gray and Livingston (points). Right panel: comparison of the variations of the line depths at CD (dotted line) of the three lines with the no-magnetic contribution (solid line), determined by the differences between the FD variations and the AR contribution. All the dare are obtained by smoothing them over 1 year.

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 ascrible 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

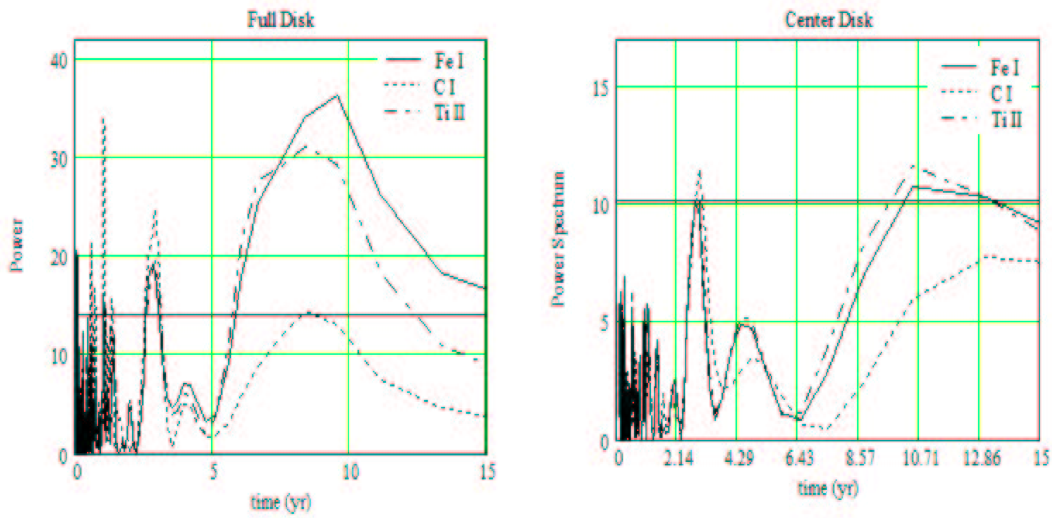

Fig. 3. Power spectra obtained by Lomb periodogram for the observational line depth data at full-disk (left) and at center-disk (right) of the all three lines. The error confindence limit of 99% is reported.

motion.
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 dara are less numerousus and more clear: the only periodicity of 2.8-2.9 yr is shared by all the lines, while a periodiciyt 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 periodicitis 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 substancial 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)*
10.8*yr*	10.4*yr*	9.5*yr*	10.4*yr*
5.45*yr*	5.55*yr*	–	5.45*yr*
–	4.13*yr*	4.68*yr*	3.83*yr*
3.25*yr*	3.20*yr*	3.25*yr*	3.24*yr*
2.7*yr*	2.7*yr*	2.4*yr*	2.6 – 2.86*yr*
2.17*yr*	2.2*yr*	–	2.15*yr*
1.8*yr*	1.8*yr*	1.76*yr*	1.8*yr*

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_{eff} alone, while a line depth can depend on the gravity, on the abundance, and on the value of microturbulence.

Acknowledgements. We acknowledge data from the VIRGO Experiment on the cooperative ESA/NASA Mission SoHO.
The SFO is owned and operated by California State University Northridge, and is funded by the University, NASA and NSF. The author thank Chapman and Walton for having provided AR coverage factors.
Part of this work was supported by grants of CVS, sponsored by Regione Lazio.

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