PHASE RELATIONS AND OTHER DIAGNOSTICS OF SOLAR ATMOSPHERIC STRUCTURE AND DYNAMICS

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Abstract. Based on spectral observations with high spatial and temporal resolution, we discuss in this brief review the dynamic behaviour of the upper layers of the quiet solar atmosphere. A proper description of this behaviour is fundamental for the understanding (and simulation) of the temperature structure and the heating of the chromosphere, and the interpretation of such conspicuous phenomena like the chromospheric "grains". The evidence is drawn from waveforms, power spectra, and phase spectra of velocity and brightness fluctuations in numerous Fraunhofer lines formed over an extended radial range of the atmosphere. A comparison with recent predictions of simulation calculations documents the strong need to extend the simulation codes to 3-D, and also to incorporate a realistic chromosphere/coronal transition layer, to better reproduce the observations.

1. Introduction

This paper focusses on the dynamics of the quiet (i.e. non-active) solar atmosphere, and in particular on the diagnostics available to examine some current models and simulations of solar atmospheric phenomena. Only a few of the observations I am going to discuss are new, most of them have been shown before; in any case it appears useful to provide some elementary background to introduce the following discussion.

It is a widespread creed that the wakes of sub-photospheric *p*-modes and convective perturbations pass through the photosphere as evanescent or running waves (depending on frequency) into the upper chromospheric layers, where running waves form shocks, and dissipate an amount of mechanical energy that is still being debated. The shocks become visible e.g. as K_{2v} bright points (or "grains") which populate the chromospheric internetwork regions with an average density of 1 grain in (5 - 10 arcsec)^2 at any time. These grains have the tendency to brighten repeatedly at intervals of 3 min for 10 to 30 sec with variable amplitude (Rutten & Uitenbroek, 1991; cf. also Fig. 5 in Gaizauskas, 1985).

It has been suggested (see the following review by Carlsson & Stein, these proceedings) that the temperature rise (in the internetwork regions) of semi-empirical

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models of the chromosphere is a result of the non-linear response of the *intensity* radiated by the shock region to the local temperature perturbation ΔT. In reality, therefore, the mean temperature gradient with height may be flat, or even negative. Highly advanced calculations (Carlsson & Stein, 1994) appear to support this picture. Certain details, like the observed periodicity of the grains, the asymmetric shape of the wave forms, and the typical evolution of the chromospheric line profiles, during the appearence of a grain in the field of view, can be reproduced with impressive similarity.

Yet, we believe that the *similarity* of these simulations with observation is misleading. Our doubts are chiefly based on a class of diagnostics that have not yet been applied rigorously to the simulations, and that appear to invalidate some of the conclusions reported there.

2. Observations and Diagnostics

2.1. WAVEFORMS

Evidently, typical waveforms of radial velocity wavetrains with amplitudes > 2 km/s deduced from measurements of Dopplershift in chromospheric lines are asymmetric (cf. e.g. Fleck et al., 1994; Hofmann et al., 1996). The slope from maximum downward velocity to maximum upward velocity is steeper than the complementary part of the cycle. However, only in exceptional cases can the asymmetry be characterized by a down-to-up ratio exceeding the value of 2:1. In most events with strong asymmetry, the observed Ca K core displacements correspond to velocities of typically ±5000 m/s, and are accompanied by a brightening of the K_{2v} feature ("grain") by a factor of 2 to 3 (see Fig. 2 in Fleck et al. 1994, or Fig. 3 and 4 in Hofmann et al., 1996).

In contrast, calculations (Carlsson & Stein, 1993) predict extended wavetrains with almost discontinuous wavefronts, formed periodically as low as at the level of the infrared Ca 8542 line. The average core displacement amplitudes in the simulated 5 cycle wavetrain are about ±4000 m/s in Ca 8542, and ±8000 m/s in Ca H_3, i.e. even much larger then those extreme observed values quoted above. Also, steep wavefronts like in the simulated wavetrain have never been observed. One might conclude already from this comparison between observed and predicted waveforms and amplitudes that the formation of shocks in the upper chromosphere is less important than theory suggests. However, we need to be aware of the effects of *seeing* in groundbased observations, that degrade the spatial resolution. Even the temporal resolution may suffer potentially from the transfer effects caused by the finite width of the velocity contribution function on the line shape.

2.2. WAVE PROPAGATION

A much more powerful diagnostic can be obtained from an observational analysis of the characteristics of the vertical propagation of wave packets in the solar atmosphere (e.g. Deubner, 1995). The calculation of phase difference spectra comparing the variations of Doppler shift at different levels in the atmosphere as function of frequency (V–V spectra) permits a conclusive characterisation of the wavetrain in terms of standing or running waves, direction of propagation, etc. Observations of this kind have been obtained to date by many authors for a large number of spectral lines covering the whole vertical extent of the visible atmosphere. Observations including also the transition region and lower corona accessible by the SUMER, EIT, and CDS experiments onboard SOHO are presently being explored to extend the range of wave diagnostics (see e.g. Steffens et al., 1997a).

The observations confirmed that below a level of about 1000 km above $\tau_5 = 1$ waves with frequencies less than the acoustic cutoff frequency $\nu_a \approx 5.3$ mHz are evanescent, and begin propagating (upward) only at higher frequencies, in accordance with the theory of linear waves in a stratified atmosphere. However, if one analyses pairs of lines which are both formed higher than this level (Ca 8542, Ca K, He 10830), nearly uniform phase spectra bear ample evidence that there the velocity field is dominated by non-propagating, i.e. evanescent or standing waves, independent of frequency (Lites, 1994; Bocchialini & Koutchmy, 1995; Fleck et al., 1994; for theory, cf. Skartlien et al., 1994, Fig. 4).

The evidence is further strengthened by phase difference spectra deduced from fluctuations of the intensity signal in a selected range of the line profile in correlation with the Doppler shift of the bisector of that range (V–I spectra). Again, chromospheric V–I spectra deviate significantly from the theoretical prediction, in displaying almost uniform phase distributions with phases in the range of −90° at frequencies far above the acoustic cutoff frequency, where the phase lag (V–I) is expected to converge to zero, in LTE (Fleck & Deubner, 1989).

Two arguments are frequently brought forward challenging the conclusions based on the phase spectra: 1) The phase lag obtained from ground based observations is subject to the effects of seeing (especially by image motion), at high frequencies. The phase values tend towards zero or ±180°, depending on the sign of the average *correlation* of the two signals compared (Endler & Deubner, 1983). Evidently, this argument does not apply to the observed V–I spectra, since the phases remain close to 90° or 100° at *all* frequencies. Neither can these phases be altered by poor spatial resolution alone. On the other hand, the characteristic frequency dependence of those V–V spectra which connect to at least one photospheric line differs strongly from those obtained with the combination of two chromospheric lines. Note that all the time series used in this comparison (Fleck et al., 1994) were taken strictly simultaneously with the same instrument. 2) The other argument applies primarily to the V–I spectra, in pointing out correctly that intensity (brightness) is a very poor if not misleading proxy of temperature under the non-LTE conditions of the solar chromosphere. At the present state of the discussion we note, however, that the V–I phase lag in the infrared Ca line simulations (Skartlien et al., 1994, Fig.2), deviates systematically by 40° to 50° from the observed values.

From the evidence presented so far we infer that we observe, in the chromosphere, a regime of standing (and partly evanescent) waves with strong, near sonic velocity amplitudes in conjunction with non-linear brightness changes induced by the wave motion. Is this scenario compatible with the formation of shock waves? *How can shocks evolve in a non-propagating wave system, where all fluid elements oscillate in phase, as observations seem to imply? Or is there a mechanism, which mitigates the observable consequences of the generation of shock waves in the upper atmosphere?*

In this context it is worth noting that observed radial velocity amplitudes reach maximum r.m.s. values of the order of 2.0 to 2.5 km/s at approximately the level of formation of Ca K_3. It decreases by about $\frac{1}{2}$ in the He I 10830 line core (Fleck et al., 1994; Bocchialini & Koutchmy, 1995; cf. however Rutten, 1995). Further up, in transition region and low coronal lines, shocks or wavetrains appear to be not regularly connected with dynamic events observed in the upper chromosphere (Steffens et al., 1997b).

2.3. REFLECTION

Apart from the observational evidence mentioned already, other observations naturally lead to the discussion of the effects of reflection in the context of wave dynamics of the solar atmosphere.

2-D phase spectra obtained recently (Straus et al., these proceedings) from SOHO MDI data confirm and enhance important details of the diagnostic diagram first published by Deubner (1990), and discussed by Marmolino et al. (1993), which have led to the interpretation of the previously neglected V–I phases observed *in between* the *p*-mode ridges in terms of wave scattering, and which stress the importance of coherent partial reflection (even of evanescent waves) in this context. The effects of reflection in certain parts of the atmosphere are even more manifest in observations reported by Harvey et al. (1993), Steffens et al. (1995), and now by Jefferies et al. (this conference), which seem to imply at least one atmospheric resonant frequency (or "mode"). The time–distance analysis applied by Jefferies et al. made it possible to estimate both the reflectivity and the height of the upper reflecting layer, the latter one being close to the top of the chromosphere (2000 km).

In parallel to these beautiful demonstrations of *oblique reflection* at the chromosphere/coronal interface, now covering ℓ-values from about 80 to several thousand, we have continued exploiting the diagnostic power of the V–I and V–V phase spectra. Long after the serendipitous detection of a 180° phase jump in phase spectra of the NaD_2 and Mgb_2 line (Staiger et al., 1984; Deubner et al., 1984) we have begun a systematic search for similar features, as a function of height in the atmosphere (Deubner et al., 1996). By climbing the profile of a spectral line (NaD_2) from the bottom of the core to the outer wings, it was possible to bridge a certain range of the atmosphere (about 750 km) in steps of arbitrary finesse.

This systematic search has not only reproduced the previously observed discontinuity in the V–I spectra; another sharp discontinuity stands out in the V–V phase difference spectra of velocity signals from the core of the line compared against signals measured at a well defined position in the line wing.

These phase discontinuities occur each only at a certain wave frequency and at one distinct height of the atmosphere approached by selecting the corresponding level in the line profile. There is a rapid transition from the spectrum with the 180° discontinuity, to spectra with a much smoother phase transition generated with adjacent levels in the line profile. No discontinuities are found at other levels. We infer from these observations the presence of discrete nodal layers determined by the structural properties of the atmosphere. One must not confuse the nodal layers of the eigenfunctions of velocity, or pressure in the atmosphere with the levels where the phase discontinuities of V–V or V–I signals are detected spectroscopically. Also, in our interpretation, we take into account that in spatially averaged power spectra the observed resonances are expected to be broadened, because horizontal inhomogeneities of sound speed and/or vertical scale introduce some scatter of the nodal layer heights. This has been discussed in Deubner et al. (1996), and we shall not expand on the details here.

We recall that, to produce the distinct discontinuities, the presence of only *one* reflecting layer (on top of the atmosphere, say) is not sufficient. It would generate a continuous spectrum of standing waves with nodal layers at all heights, depending on frequency only. However, the characteristic modulation of the oscillatory power of Doppler shifts and brightness fluctuations as a function of both frequency and height as derived from the observations (Fig. 1) clearly testify to the presence of vertical resonances in the solar atmosphere.

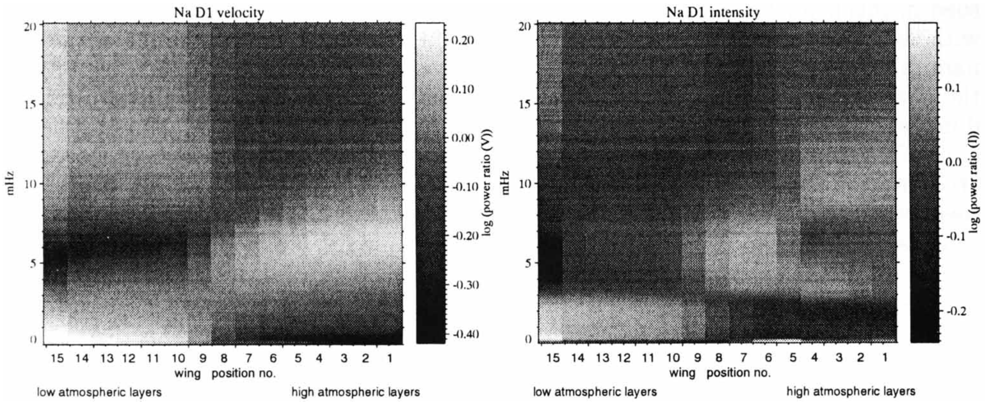

Figure 1. This diagram presents the most intuitive evidence of the vertical resonances of the solar atmosphere. Power spectra of velocity (left) and intensity (right) fluctuations in the Na D_2 line as function of *frequency*, and *height* in the atmosphere corresponding to the mean level in the line profile at which the fluctuations are measured. Note the spatial (viz. vertical) phase shifts of intensity *vs* velocity "nodes" (power minima) e.g. at 6 and 9 mHz (cf. also Fig. 8 in Deubner et al. 1996).

Worrall (1997, priv. comm.) has mentioned the possibility that in chromospheric lines like NaD_2 non-LTE effects could affect the response of spectral intensity to changes of temperature in such a way that the sign of $\mathrm{d}I/\mathrm{d}T$ changes as a function of the position in the line profile. Even though it would seem difficult to explain the distinct *frequency* dependence in the I-signal, such an effect might influence its variation with *height* in the atmosphere. Severino (1997, priv. comm.) argues, on the basis of non-LTE simulations of the NaD_2 line in static atmospheres, that within the range of the inner Doppler core a reversal of the temperature response with a maximum effect of the order of $2\,10^{-3}$ of the mean spectral intensity is expected to be observed for a 5% increase in temperature. I doubt, however, that such a tiny effect could be detected at all. Regarding V–V phase discontinuities, a reversal of Doppler shift, in response to a given velocity perturbation, with height in the atmosphere is not easily visualized, in particular in those parts of the line profile (formed in the lower photosperic layers), where the lower level contribution to the V–V phase difference is discontinuous.

3. Discussion

3.1. THE TEMPERATURE STRUCTURE OF THE ATMOSPHERE

Understanding the structure of the solar atmosphere, transition region, and corona is fundamental for a proper understanding of the physical processes in those layers of the sun that are most directly involved in solar-terrestrial relations. Since the very same layers can be directly inspected whenever the sun shines, the problem of modelling the underlying physics should appear an easy task. In reality, it is not. Rather, it has become one of the major challenges in solar physics, resisting even the most advanced theoretical tools available.

We have already laid out the two lines of approach which are presently being pursued in this field: 1) Multi-line observations with high spatial and spectral resolution, with sufficient temporal resolution to capture the relevant frequency range of the dynamics involved, and with sufficient spatial coverage: to preserve the 3-D aspects of the observed phenomena; to distinguish various sources of dynamic phenomena, or different conditions in the atmosphere; and to enhance statistics. 2) Non-adiabatic, non-LTE computer simulations of wavetrains in a realistic solar atmosphere, based on an excitation model guided by observations. The agreement between observation and theoretical prediction is not satisfactory, as we have seen above. In fact, it is poor; the conclusions from the two lines of approach differ fundamentally with regard to basic behaviour of the solar atmosphere.

We have mentioned above certain deficiencies of the data: limited vertical and horizontal resolution due to seeing and radiation tranfer effects, and inadequacy of the spectral *intensity* as a proxy for *temperature* for the interpretation of the chromospheric V–I phase diagrams. The simulation results of Carlsson and Stein, on the other hand, suffer from several constraints to the computer code which could easily bias the conclusions (cf. however Cheng & Yi, 1996): 1-D geometry, transmitting upper boundary (without transition layer), and a source of perturbations which is inconsistent with the geometry, because it is derived from the observed 3-D superposition of a large number of non-radial wavemodes. The first two constraints are severe because they modify drastically the conditions for reflection at the upper boundary, and, therefore, the character and amplitude of the waves in the wavefields below the boundary, and above. With regard to the drastic physical consequences of such unrealistic conditions, it is highly desirable to explore other model calculations, which permit to relax the limitations of the Carlsson/Stein code. Since computer power presently limits all attempts to complete such simulations with sufficiently realistic models, Steffens et al. (1997c) have solved numerically in 3-D the linear adiabatic wave equations for a VAL atmosphere, including the convection zone down to 10^4 km below $\tau_5 = 1$, and a realistic transition zone and corona up to $1.7\,10^4$ km. Several chromospheric temperature distributions were chosen to account for various modifications of the VAL atmosphere, recently suggested, and to study their effects on properties of the wavefield.

The results of this work are rather encouraging. The $k-\omega$ diagrams derived from this 2-D study reveal significant resonances in the range close to and above the acoustic cut-off frequency, particularly near 6 and 8 mHz. These resonances resemble closely in position and in shape the "chromospheric mode" detected by Harvey et al. (1993), and, seen as a "ridge", by Steffens et al. (1995). They are also strangely reminiscent of the secondary peaks in high resolution power spectra of photosperic and chromospheric Fraunhofer lines in earlier studies (Deubner, 1976), attributed erroneously to *optical* filtering effects of the actual velocity or intensity contribution functions. The frequency of these resonances is only weakly dependent on wavenumber as expected, since they are thought to reside chiefly in the atmosphere; the slight upward bend of the ridges at higher wavenumbers is first noticeable at $k \approx 1.5$ rad/Mm ($\ell \approx 1000$). Generally, however, the occurrence of the resonances appears to depend only moderately on the details of the model of the atmosphere employed by the authors (Steffens et al., 1997c).

These results suggest strongly that a potential well for acoustic waves, formed by the transition region together with the convection zone and atmospheric structure, succeedes in trapping sufficient acoustic power to give rise to well defined resonant features in spectra and $\nu - \ell$ diagrams of photospheric and chromospheric oscillations. These resonances also provide the most compelling explanation of the phase discontinuities discussed in Sec. 2.3.

3.2. CONCLUSIONS

In the debate over the energy balance of the quiet solar atmosphere, an assessment of the net amount of energy flux carried by acoustic waves, and how it is distributed, is of importance. It is yet uncertain, owing to intrinsic difficulties in correcting the measured amplitudes for insufficient temporal or spatial resolution, how much power the sun actually feeds into high frequency ($\geq$10 mHz) perturbations of the mean atmosphere. However, the observations seem to suggest that, in the chromosphere, highly non-radial waves within a range of periods rather closer to the acoustic cut-off frequency, and with a degree typically of the order of $\ell = 1000$ (viz. the K_{2v} bright points) are closely linked with the process of converting mechanical into radiative energy. These conditions call for a very careful scrutiny of the chromospheric dynamics.

We have seen no observed phase relations yet which support the notion of travelling acoustic waves in the chromosphere. On the contrary, the observed phase spectra derived from Doppler shifts and brightness fluctuations (with due caution regarding the limited value of brightness as a proxy for temperature) deviate significantly and systematically from predictions of advanced calculations with running acoustic waves and ensueing shocks. The observed waveforms do *not* regularly exhibit the discontinuous wavefronts as shown in these simulations, nor do they reach amplitudes nearly as high as predicted. Rather, the observational diagnostics that we have discussed here imply a coherent scenario with a significant if not dominant contribution to the wavefield of resonant (i.e. standing) wave trains maintained by the resonant structure naturally provided with the transition region as upper boundary. It should be noted that the time–distance analysis of Jefferies et al. (1997, and these proceedings), yielding a reflection coefficient $R \leq 9\%$, is based on spatially filtered data with $\ell \approx 125$, whereas the effective degree of the waves seen in high resolution observations used to study the Ca K grains is rather higher than $\ell \approx 1000$, which would seem to entail much better (if not total) reflection.

In conclusion, it appears that at some distance from supergranular lanes or compact magnetic fields the character of the chromospheric waves is less dramatic than what is implied from most 1-D simulations. Even observed radial velocities of ~ 6000 m/s are of little concern in a standing wave system, where all fluid elements move in phase, and *return* in phase after half a period, as evidenced in the observations. The conspicuous spatial and temporal intermittency of the Ca K grains can still be understood as a consequence of interference and compression at nodal layer crossings, enhanced by the non-linear response of the source function to temperature changes, as suggested earlier (Deubner, 1991, cf. also Rutten & Uitenbroek, 1991). The V–V phase spectra are in good, and the V–I spectra in reasonable, agreement with inferences based on the resonant standing wave model.

All this accumulating observational evidence of the 3-D structure and dynamics of the quiet solar atmosphere, in conjunction with further elaborated techniques employed for simulation of what is possibly not quite so rough a medium, should hopefully in the near future lead to an improved understanding of this important boundary of the solar body that appears so easily accessible.

References

Bocchialini, K. and Koutchmy, S.: 1995, in J.T. Hoeksema, V. Domingo, B. Fleck, and B. Battrick (eds.), *Fourth SOHO Workshop: Helioseismology*, ESA, p. 499.

Carlsson, M. and Stein, R.F.: 1993, in P. Maltby and H.L. Pécsely (eds.) *Wave Phenomena in Solar Terrestrial Plasmas* Univ. of Oslo, p. 21.

Carlsson, M. and Stein, R.F.: 1994, in M. Carlsson (ed.), *Chromospheric Dynamics*, Univ. of Oslo, p. 47.

Carlsson, M. and Stein, R.F.: *these proceedings*

Cheng, Q.Q. and Yi, Z.: 1996, *Astron. Astrophys.* **313**, 971.

Deubner, F.-L.: 1976, *Astron. Astrophys.* **51**, 189.

Deubner, F.-L.: 1990, in J.O. Stenflo (ed.) *Solar Photosphere: Structure, Convection, and Magnetic Fields* IAU Symp. **138**, 217.

Deubner, F.-L.: 1991, in P. Ulmschneider, E.R. Priest, and R. Rosner (eds.) *Mechanisms of Chromospheric and Coronal Heating*, Springer, p. 6.

Deubner, F.-L.: 1995, in R.K. Ulrich, E. Rhodes, Jr., and W. Däppen (eds.), *Helio- and Asteroseismology from the Earth and Space*, ASP Conf. Series **76**, 303.

Deubner, F.-L., Endler, F., and Staiger, J.: 1984, *Mem. S. A. Ital.* **55**, 135.

Deubner, F.-L., Waldschick, Th., and Steffens, S.: 1996, *Astron. Astrophys.* **307**, 936.

Endler, F. and Deubner, F.-L.: 1983, *Astron. Astrophys.* **121**, 291.

Fleck, B. and Deubner, F.-L.: 1989, *Astron.Astrophys.* **224**, 245.

Fleck, B., Deubner, F.-L., Hofmann, J., and Steffens, S.: 1994, in M. Carlsson (ed.), *Chromospheric Dynamics*, Univ. of Oslo, p. 103.

Gaizauskas, V.: 1985, in B. W. Lites (ed.), *Chromospheric Diagnostics and Modelling*, Sunspot, N.M., p. 25.

Harvey, J.W., Duvall, T.L., Jefferies, S.M., Pomerantz., M.A.: 1993, in T.M. Brown (ed.) *GONG 1992: Seismic Investigation of the Sun and Stars*, ASP Conf. Series **42**, 111.

Hofmann, J., Steffens, S., and Deubner, F.-L.: 1996, *Astron. Astrophys.* **308**, 192.

Jefferies, S.: *these proceedings*

Jefferies, S., Osaki, Y., Shibahashi, H., Harvey, J.W., D'Silva, S., and Duvall, T.L., Jr.: 1997, *Astrophys. J.* **485**, L 49.

Lites, B.: 1994, in M. Carlsson (ed.), *Chromospheric Dynamics*, Univ. of Oslo, p. 1.

Marmolino, C., Severino, G., Deubner, F.-L., and Fleck, B.: 1993, *Astron. Astrophys.* **278**, 617.

Rutten, R.J.: 1995, in J.T. Hoeksema, V. Domingo, B. Fleck, and B. Battrick (eds.) *Fourth SOHO Workshop: Helioseismology*, ESA, p. 151.

Rutten, R.J. and Uitenbroek, H.: 1991, *Solar Phys.* **134**, 15.

Severino, G.: 1997, *private communication*

Skartlien, R., Carlsson, M., and Stein, R.F.: 1994, in M. Carlsson (ed.), *Chromospheric Dynamics*, Univ. of Oslo, p. 79.

Staiger, J., Schmieder, B., Deubner, F.-L., and Mattig, W.: 1984, *Mem. S. A. Ital.* **55**, 147.

Steffens, S., Deubner, F.-L., Fleck, B., and Wilhelm, K.: 1997a, in A. Wilson (ed.), *The Corona and Solar Wind Near Minimum Activity*, ESA, p. 685.

Steffens, S., Deubner, F.-L., Fleck, B., Wilhelm, K., Harrison, R., and Gurman, J.: 1997b, in A. Wilson (ed.), *The Corona and Solar Wind Near Minimum Activity*, ESA, p. 679.

Steffens, S., Deubner, F.-L., Hofmann, J., and Fleck, B.: 1995, *Astro. Astrophys.* **302**, 277.

Steffens, S., Schmitz, F., and Deubner, F.-L.: 1997c, *Solar Phys.* **172**, 85.

Straus, Th., Deubner, F.-L., Fleck, B., Marmolino, C., Severino, G., and Tarbell, T.; *these proceedings*

Worrall, G.: 1997, *private communication*