Helioseismic Spectral Diagnostics

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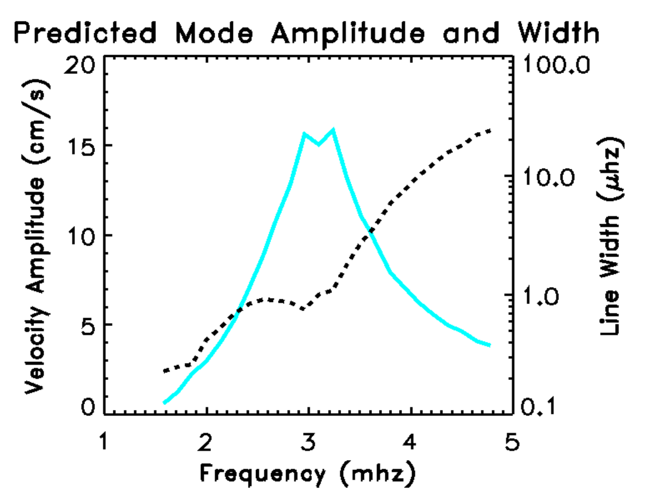
In order to test models of the excitation of *p* modes and their behavior in the visible atmosphere, we calculate time sequences of Fraunhofer absorption line profiles of the Ni, Fe, K, Na, and Ca lines used in helioseismology, focusing on Sun-as-a-star observations in this initial work. The atmospheric models, which give rise to the line profiles, are based on the VAL-C, perturbed by realistic *p*-mode eigenfunctions. The time sequences of line profiles are analyzed as for various instruments, to compare predicted and observed mode amplitudes as a function of temporal frequency

Overview

1. **Motivation**
   While the frequencies of the *p* modes used as probes of the solar interior can be calculated to high precision, and are in quite good agreement with observations, our ability to predict the amplitudes of the modes is in a much more rudimentary state; yet the amplitudes – and widths – of the *p* modes offer significant constraints on the motions and thermodynamic fluctuations in the outer convection that excites the modes, and the variation of the amplitude with height in the visible atmosphere affords an important test of our understanding of the formation of the spectral line diagnostics upon which all of our helioseismic knowledge resides.
2. **Static approach**
   The variation of the height of formation (in a static atmosphere) across the spectral line profile is used to estimate the altitude in the solar atmosphere where the observed seismic signal is formed. From the vertical variation of the *p*-mode eigenfunctions, the mode energy and excitation rate (intrinsic characteristics of the modes) can be estimated for the different observational methods.
3. **Dynamical approach**
   Time-varying spectral line profiles are computed from an oscillating solar atmosphere, with the calculated *p*-mode eigenfunctions and amplitudes, from which the velocity that would be measured by the different instruments' techniques can be obtained and compared with observation.
4. **Helioseismic Velocity Measurements**
   These two methods are being applied to measurements from GONG, BiSON, SOHO/MDI, SOHO/GOLF, MOTH, and SDO/HMI.

Excitation

The rate of excitation of the modes is based on adiabatic eigenfunctions, for the time being, from a CESAM solar model with an extended atmosphere. The convective fluctuation which excite the modes come from a realisitic three-dimensional calculation based on the code of Stein and Nordlund. The amplitudes are derived from the excitation rates using the lifetimes as measured by the GOLF experiment (the series known as BW1 at the minimum of solar activity) and the mode masses evaluated at $\tau = 1$.



Eigenfunctions: Time-dependent convection treatment

To determine the non-adiabatic eigenfunctions in solar-type stars, it is fundamental to take the time-dependent coherent coupling between convection and oscillations into account. More precisely, in the very superficial layers of the Sun, typically between $\log T = 4.2$ and the photosphere: the thermal relaxation time, the oscillation periods of solar *p*-modes, and the time-scale of most energetic convective elements are of the same order. Hence, the oscillations are highly non-adiabatic in this region; and the time variations of convective quantities (convective flux, turbulent pressure, ...) play a major role in determining the shape of the eigenfunctions and the damping rates of the modes

For our non-adiabatic computations, we use an improvement of the time-dependent convection treatment of Gabriel (1996), which is a local perturbative treatment following the mixing-length approach of Unno (1967). The first improvement is that proposed by Grigahcene *et al.* (2005), where an additional parameter β is introduced in the perturbation of the thermal closure equation. In the present computations, the value $\beta = -1.5\, i$ is adopted. The second improvement is to follow a non-local approach similar to that of Balmforth (1992). In this approach, local and non-local convective quantities are related by equations of the form:

$$F_{c,\,nl} P_0 = \int_{-\infty}^{\infty} F_{c,\,l}\, e^{(-a|\log P - \log P0|)}\, d \log P.$$

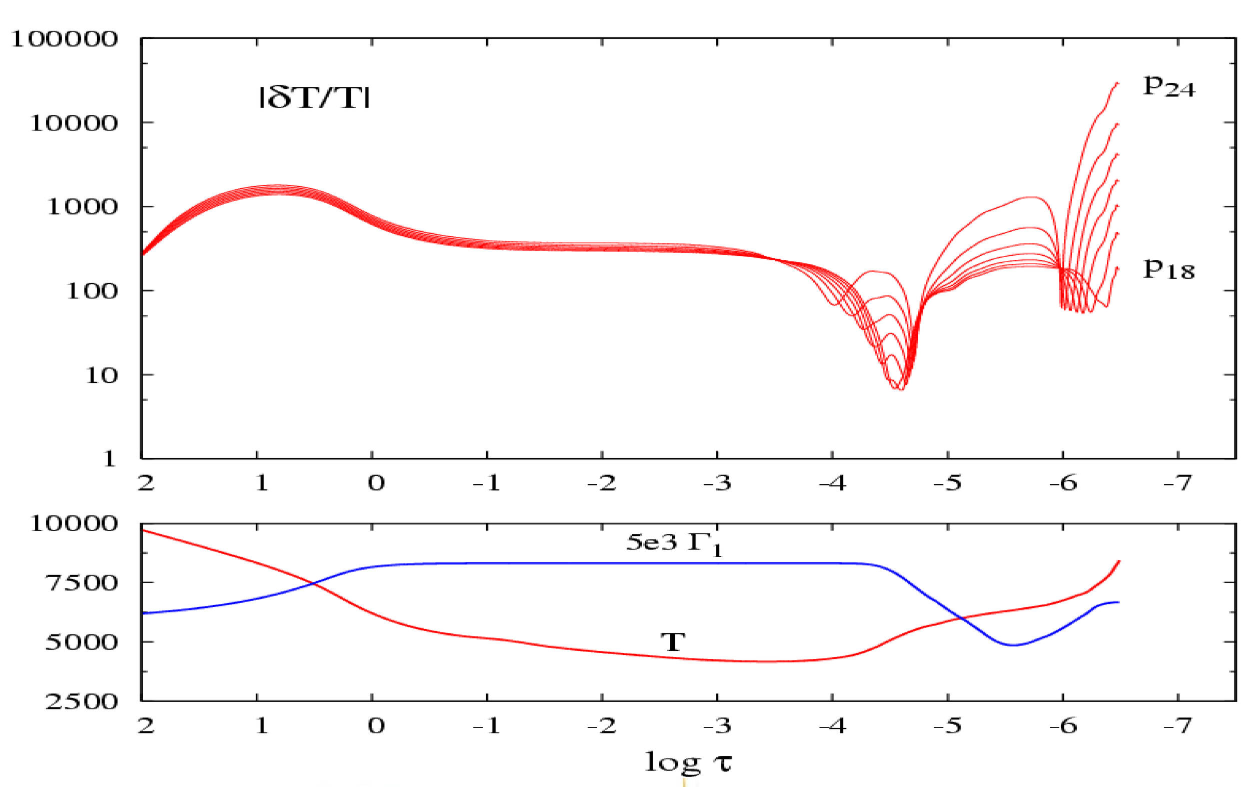
These equations are applied to the convective flux, turbulent pressure, and the super-adiabatic gradient. The corresponding non-local parameters *a* (for the convective flux) and *b* (for the turbulent pressure) used in the present study are those giving the best agreement with the results of 3D hydrodynamic simulations by Stein & Nordlund (1998): $a = 6.325$ and $b = 1.706$ (Dupret *et al.* 2006). For the super-adiabatic gradient non-local parameter, we take $c = 2$. With this set of parameters, good agreement with the observed solar damping rates and phases is obtained (Dupret et al., 2006).

Eigenfunctions: Atmosphere treatment

The diffusion equation is not valid in the atmosphere and the non-adiabatic modeling of the oscillating atmosphere adopted here is that proposed by Dupret *et al.* (2002). It is based on the fact that the thermal time scale is much shorter than the oscillation periods in the atmosphere, so that the atmosphere adapts quasi-instantaneously to the acoustic perturbations.

We use an equilibrium solar atmosphere model (VAL). The increase of the temperature high in the atmosphere ($\log \tau \leq 4$) present in this model significantly affects the shape of the eigenfunctions; because of the associated steep drop of Γ_1 (see the lower panel in the figure below), additional trapped modes appear in this region. Turbulent pressure associated with convective motions in the overshoot region is present in this atmosphere model; we take its time variation into account in our non-adiabatic computations. Turbulent pressure associated with magneto-chromospheric effects is also present in the outermost layers, however we neglect its time variations.

We applied the above treatment to the determination of the non-adiabatic eigenfunctions for all of the modes from 1500 μHz to 5000 μ Hz with $0 \leq \ell \leq 4$. In the top panel of the figure below we give as an example the eigenfunction $|\delta T/T|$ (Lagrangian) obtained for the radial modes p_{18} to p_{24} as a function of the logarithm of the Rosseland optical depth. The radial displacement $\delta r/R$ is normalized to 1 at $\tau = 0.1$. The shape of $|\delta T/T|$ is mainly determined by the effect of the optical depth Lagrangian variation due to the oscillations $\delta T/T \sim$ constant + $\partial \ln T/\partial\tau\ \delta\tau$). In the lower panel, we give the equilibrium temperature and Γ_1 .



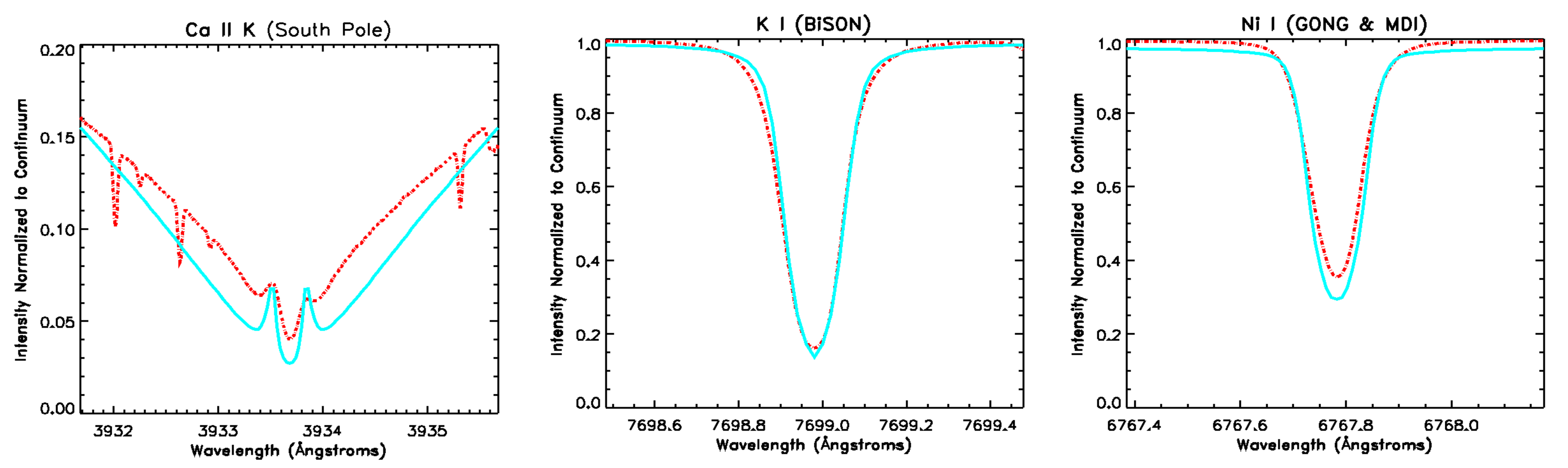
Fraunhofer Line Profiles

The numerical code contains two parts: the first computes the static mean atmosphere from the basic data of temperature and micro-turbulent velocity as a function of column mass. It solves simultaneously the equations of hydrostatic equilibrium, radiative transfer and statistical equilibrium for a 20 level plus continuum hydrogen atom. The output of this computation includes: pressure, density, electron density and altitude as functions of the column mass. Then, the static profiles of different spectral lines are computed, for the following elements: sodium, potassium, calcium, iron and nickel. All of these elements are treated out of LTE, at the exception of iron. Partial frequency redistribution effects are taken into account for calcium resonance lines only. (for more details see the table)

The second part of the codes computes the profiles of the same lines at different times of the oscillation. At each time, perturbation of velocity, temperature and density are computed for the different layers of the atmosphere, from the eigenfunctions of the oscillation modes under consideration. These perturbations are added to the rest values of the corresponding variables. Then, the code solves the same equations as above, excepted hydrostatic equilibrium, to determine missing variables.

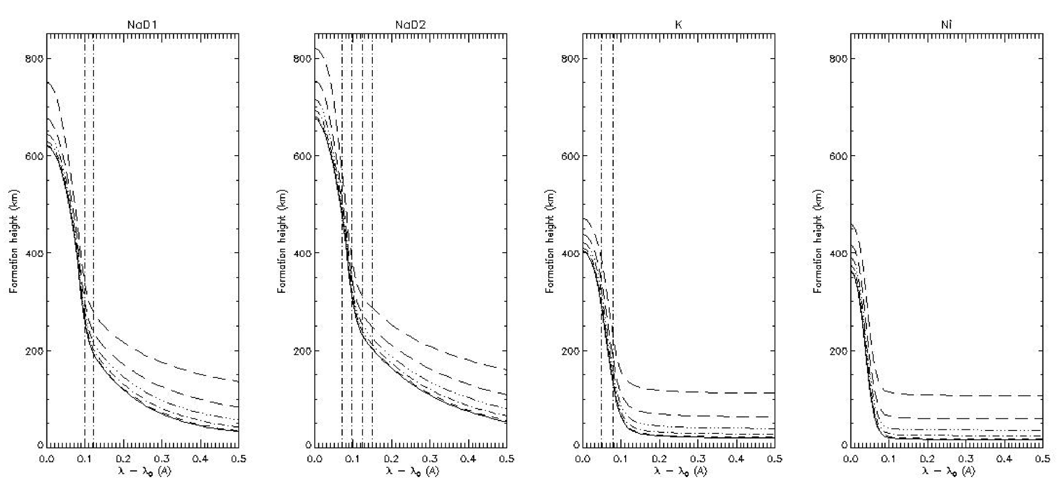
Element	*Num levels*	*wavelength (Å)*	*NLTE ?*	*method*	*Redistribution*
11 Na	4	5890, 5896	NLTE	ETLA	CRD
19 K	4	7699	NLTE	ETLA	CRD
20 Ca	7	3934	NLTE	ETLA	PRD
26 Fe		6173	LTE		
28 Ni	11	6768	NLTE	MALI	CRD

ETLA: equivalent two-level atom
MALI: multilevel accelerated Λ-iteration
PRD: partial redistribution
CRD: complete redistribution

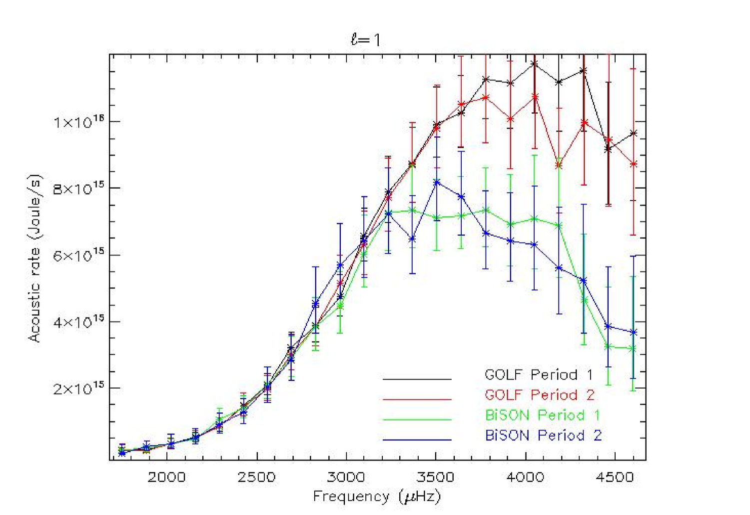


Static Approach

This approach has been used by Baudin *et al* (2005, A&A, 433, 349) but treated in a coherent way (same code). The excitation rates of the modes were computed from GOLF and BiSON observations (data are coeval or very close in time at worst). Excitation rates of GOLF and BiSON are in agreement for the low-frequency part of the spectrum but disagree at high frequency. Different reasons can explain this disagreement. Among them: an incorrect extraction of mode parameters at high frequency, or errors in the eigenfunctions at high frequency.



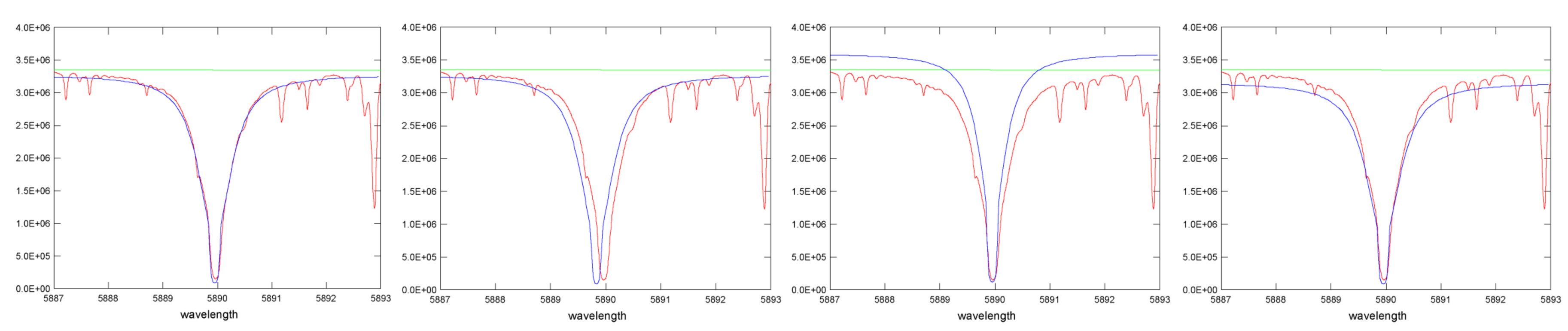
Height of formation versus the position in the wing of the line for the Na D lines (GOLF), K line (BiSON), and Ni line (GONG and MDI). The dotted lines indicate where the respective instruments operate (except for GONG which uses the entire profile)



Excitation rate computed from GOLF and BiSON observations

Dynamical Approach

We are in the process of calculating the time-varying atmospheres and line profiles, integrating them over the solar surface, and applying the measurement algorithms to extract the inferred velocities. Examples of such time-varying profiles for the Na D_1 line are shown below.



Unperturbed profile *Uniform Velocity Perturbation* *Uniform Temperature Perturbation* *Uniform Density Perturbation*

Acknowledgments

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