MICRO- AND MACROTURBULENT MOTIONS AND THE VELOCITY SPECTRUM OF THE SOLAR PHOTOSPHERE

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Abstract. A given motion field in a stellar atmosphere is usually observed through ‘filters’ defined by line shifts and -broadenings and conventionally called macroturbulence and microturbulence. These ‘filters’ can be defined and computed exactly, as a function of the wave number of the velocity field (Figure 1).

We apply the results to several cases of an assumed motion field spectrum, and to observations of broadenings and displacements of solar Fraunhofer lines formed at a depth \( \tau_5 = 0.1 \) (Figure 2).

The results show that virtually all energy of the photospheric motions at that level is contained in a small range of wavenumbers, corresponding to the observed distribution of granular cell diameters. In other words: a well-developed spectrum of hydrodynamical turbulence extending over a large range of wavelengths does not exist at that level of the photosphere.

I. Introduction

In the solar photosphere and chromosphere three kinds of motions may occur; they manifest themselves in the profiles of the Fraunhofer lines. By systematic large-scale unstationary convective motions hot gas moves upward and cool gas goes downward. In the solar photosphere these motions seem to penetrate up to slightly above \( \tau_5 = 0.1 \) (De Jager and Neven, 1967).

In laboratory experiments and in the Earth’s atmosphere such convective motions can generate smaller-scale turbulent motions where the convective kinetic energy is transmitted to motions at larger wave numbers by the action of the non-linear terms in the equations of motion; the energy is eventually dissipated by viscosity in the motions of the smallest geometrical scale.

Thirdly, out of this turbulent medium waves seem to propagate upward. Together, the systematic and the turbulent motions may be described by the notion: turbulence spectrum of the photosphere, or the photospheric motion field.

The observation of these motions relies on the determination of wavelengths and profiles of spectral lines, and meets with the difficulty that in solar spectral observations a sufficient spatial resolution can usually not be obtained. Even in the case of so-called high spatial resolution a resolution of one or a few seconds of arc seems the best attainable. Hence the observed spectral line profiles are not only the results of integration over the depth of the photosphere but also over part of the surface.

The techniques for investigating these motion fields fall into two categories: For

* By \( \tau_5 \) we mean the monochromatic optical depth in the continuous spectrum at 5000 Å.
the investigation of the large scale ('macroscopic') components the classical curve-of-growth analysis now seems outdated; clearer information is obtained by investigating line asymmetries or displacements on spectrograms of high spatial resolution. The small-scale ('microscopic') motion component is usually investigated with methods like that of Goldberg-Unno. Up to now astrophysical methodology has developed two 'filters' for observing the motion field. One of these 'filters' is conventionally called microturbulence, the other is called macroturbulence. Part of the spectrum of motions contributes to the microturbulent broadening; another part to the macro-turbulent displacement and broadening. Neither the microturbulent nor the macro-turbulent velocity components as deduced from the observed line profiles, are equal to the true rms velocity component; both are smaller. In this paper we define these 'filters', and investigate their significance for spectrally and spatially high resolution observations and we examine whether the actual spectrum of motions can be deduced from such observations.

2. Assumptions and Definitions

In Section 3 we shall compute the 'transmission' of the micro-turbulence and macro-turbulence 'filters' for different values of the wavenumber \( k \). The assumptions on which the computations are based are summarized below:

(a) We assume a weak and infinitesimally narrow spectral line, neglecting other causes for line widening.* The ratio \( p \) between the total line absorption coefficient \( \kappa_l \) and the continuous absorption coefficient \( \kappa_d \) is assumed constant with depth; \( p \leq 1 \).

(b) The relation between the optical and the geometrical depths is approximated by

\[
d \log \tau = \alpha \, dh \quad \text{or} \quad dh = \theta \, d \log \tau \quad \alpha^{-1} = \theta
\]

with \( \alpha \) = constant, which applies in very good approximation to many stellar photospheres. In the solar photosphere, between \( \tau_5 = 10^{-4} \) and 0.6: \( \alpha^{-1} = 140 \) km, with a largest deviation of 10 km; we shall call \( \alpha^{-1} = \theta \) the optical scale height.

(c) We assume that the line is formed by pure absorption and that the source function is a linear function of depth.

(d) We assume the velocity field to be decomposed according to Fourier for each of the cartesian coordinates; for this motion field we introduce the wavelength \( L \), the wavenumber \( k = 2\pi L^{-1} \), and the half-amplitude \( A_k \) of the sightline velocity component \( \zeta(k) \) with wavenumber \( k \). Hence, along any vertical line in the solar atmosphere:

\[
\zeta(k, h) = A(k) \sin(kh + \beta_k), \quad (2a)
\]

where \( \beta_k \) is an arbitrary phase, dependent on the position on the disk. Note that

* This is done, simply, to separate the broadening due to the motion field from other broadening causes, which are irrelevant in this connection. The assumption does not restrict the subsequent discussion.