DIFFERENT MODES OF TURBULENCE IN THE ACTIVE REGIONS OF THE SOLAR PHOTOSPHERE

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ABSTRACT. In work the range of different methods for the analysis of characteristics of turbulent processes in the active regions of the solar photosphere has been used. The changes of fluctuations distribution function and its moments were analyzed, spectral analysis was carried out.

It was found out from the observations of active region carried out with the 70-cm vacuum tower telescope VTT in Isanie (Tenerife Island, Spain) that the turbulent processes in the sun photosphere are characterized by two different spectra of turbulence. The first one of them is well known Kolmohorov spectrum, which describes the plasma with zero mean magnetic field. The second one is the Kraichnan spectrum with a different from zero mean magnetic field. Transition from one spectrum type to another one occurs at scale of 3 Mm.

We have to note that the scale 3 Mm corresponds to one of mesogranulation and testifies about non-zero mean magnetic fields for the consideration of regions exceeding the granulation in active regions of the photosphere. Besides, this clears the possibility of appearance of self-organizing magnetic plasma structures such as spots, active regions and complexes of activity.

Key words: solar photosphere, turbulent processes in the sun photosphere, turbulent model, self-organizing magnetic plasma structures, mesogranulation.

1. Introduction

Studying the statistical and spectral properties of velocity fields makes it possible to determine the role of turbulent processes in the interaction between plasma flows and reveal the real mechanisms of the energy and magnetic field transformation

In this work, we consider the features of turbulent processes and their relation to the average magnetic fields in the solar photosphere. This is important for understanding the many processes studied in solar physics, magnetosphere of the stars and planets.

A classical approach to studying the statistical properties of a turbulent flow consists in calculating structural functions with local scale *l* (distribution function statistical moments) of different orders. Kolmogorov's theory [Kolmogorov, 1941] (K41) predicts the Gaussian statistics of homogeneous isotropic turbulence and the power law dependence for structural function

$$S_q(l) = \left\langle \left| \upsilon(x+l) - \upsilon(x) \right|^q \right\rangle \sim l^{\zeta(q)},$$

in the inertial range when the Reynolds numbers are large, where $\langle \ldots \rangle$ is averaging over an ensemble. When Kolmogorov (1941) postulated that structural functions only depend on the energy dissipation scale and rate, he deduced that the energy flux spectrum depends on wave number k as $E_K \sim k^{-5/3}$. This law relatively adequately describes the spectrum with developed isotropic hydrodynamic turbulence; however, more precise measurements of turbulent flows indicated that the exponent differs from 5/3. This discrepancy was related to the presence of structural inhomogeneity of a turbulent process (intermittency) [Novikov and Stewart, 1964]. Random pulsations in an intermittent medium have a distribution function different from the Gaussian distribution.

We should note that plasma in a strong magnetic field is described by an approach, which allows for a consideration of the dynamics in the plane across the magnetic field in the scope of a two dimensional model. This model is illustrated by the Iroshnikov–Kraichnan two dimensional model (IK) of MHD turbulence [Kraichnan, 1965], which is very often used to interpret properties of turbulent boundary plasma. The energy spectrum in the Iroshnikov–Kraichnan model is defined by the relation $E_{IK}(k) \propto k^{-3/2}$. In comparison with the Kolmogorov spectrum, this spectrum exhibits a significantly reduced level of energy transfer on small scales, perturbations of MHD variables propagate at a speed of the order of the Alfven speed.

In spite of the fact that analytical methods have been developed in the theory of turbulence, they are not as detailed and accurate as semiempirical models that are based on statistical methods. This is of special importance in cases when turbulence with intermittency is described, because not only intermittency results from inhomogeneous turbulence, but inhomogeneity itself is also distributed chaotically.

2. Used observational data

For the statistical and spectral analysis, we used solar active region observations obtained on November 13, 2007, at the German vacuum tower telescope (VTT) [Schroter et al., 1985] at Izaña (Tenerife, Spain) in three wavelength ranges: Fe I λλ 1564.3–1565.8 nm, Ba II λ 455.4 nm, and Ca II λ 396.8 nm an active region (facula) near the solar disk center. The spatial resolution was 0.185″.

Following the standard procedure, all the images were corrected for the dark current, variations in the transparency of Earth's atmosphere, and different sensitivities of CCD camera pixels. The subsequent processing of the observational data included the finding of the velocity at the center (height in the solar atmosphere of h = 650 km) and in the farout wings (h = 0) of the Ba II line. For this purpose, we used the lambda meter procedure [Stebbins and Goode, 1987].

The parameter fluctuations of the velocity field are due largely to convective and wave motions. To distinguish between the granulation and wave components of the velocity field, we built a diagnostic diagram k – ω, i.e., the dependence of the power of the δV variations on the temporal (ω) and spatial (k) frequencies [Kostyk and Khomenko, 2002]. In this work we used only the convective velocity field component (Fig. 1).

3. Determination of the type of turbulent processes

For the identification of the turbulence we used the function of the probability density of fluctuation amplitudes of the velocity *P(dv,l)*. It should be noted that, the random noncorrelated fluctuations of the difference of measured velocities between the observations, shifted in space, will be described by the Gaussian distribution. For the turbulence with intermittency the probability of considerable fluctuations on distribution's wings will be rather high due to excess energy of large scale disturbances.

The distribution functions of *P(dv,l)* are shown in Fig. 2. Narrow wings of the distribution function indicate on the homogenity of turbulent processes, which pertains both to the Kolmogorov type and Iroshnikov–Kraichnan type processes [Kozak et al., 2008, Budaev et. al., 2011, Kozak et al., 2012]

To determine the type of turbulent processes, we analyzed the moments of the probability density function for different orders. In the turbulence theory, this commonly used analysis is referred to as extended self-similarity (ESS) analysis [Benzi et al., 1993]. It allows researchers to considerably narrow down the possible types of turbulent processes.

In a case of fully homogeneous isotropic Kolmogorov 3D (K41) turbulence the values of exponent are defined by a relationship $\zeta(q) = q/3$ [Frisch *et al.*, 1978], and for the Iroshnikov-Kraichnan model (IK), which describes plasma turbulence in the strong magnetic field, $\zeta(q) = q/4$ [Kraichnan, 1965].

The main idea of this approach is to find dependences of a relative value of power index for the different structure function orders. In the general case, for q-th and p-th orders the following relationship is assumed:

$$S_q(\tau) \sim S_p(\tau)\ \tau^{\varsigma(q)/\varsigma(p)}.$$

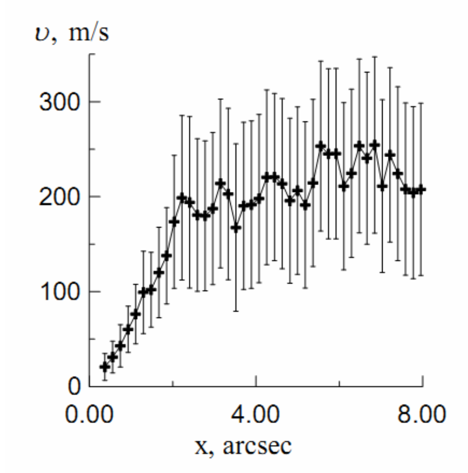

Figure 1: Observed velocity fluctuations in active regions (h = 650 km).

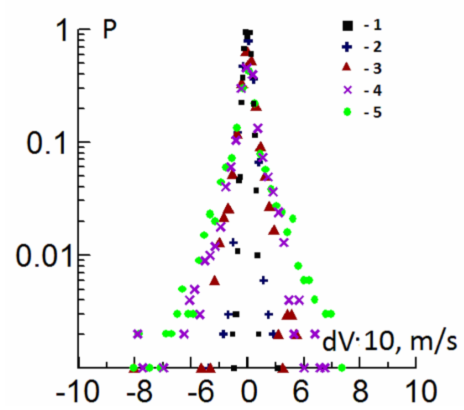

Figure 2: Distribution functions P of probability density of velocity fluctuations for various spatial shifts *l* (1 – 0.185 arcsec, 2 – 0.37 arcsec, 3 – 0.74 arcsec, 4 – 1.11 arcsec, 5 – 1.85 arcsec).

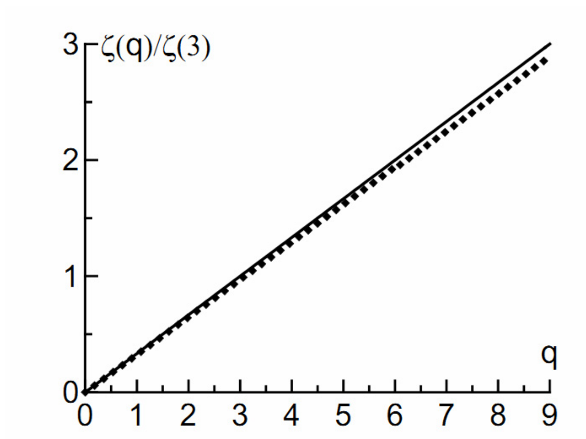

Figure 3: The ratio of the structural function of the qth order to the structural function of the third order: dots are the observations; the continuous line shows the model values calculated by the Kolmogorov model.

Once such dependence is found, it is compared with the analogous dependences for different turbulence models.

For comparison with the Kolmogorov model, we investigated the ratio between the power of the moment of the qth order probability density function and the power of the third order p = 3 (Fig. 3). The ESS analysis shows a good consistency of the turbulent processes with the Kolmogorov turbulence model for q < 6.

To compare the observations with the Iroshnikov–Kraichnan model, we also analyzed the ratio between the power of the moment of the qth order probability density function and the power of the fourth order p = 4 (Fig. 4). We see that, at q > 6, the dependence is closer to the Iroshnikov–Kraichnan model. This approach does not allow us to determine the scale of transition from one process to another, but we can infer that there are two distinct types of turbulence.

In order to refine the scale of the turbulent processes, we investigated the spectral dependences of the changes in velocity for active regions (Fig. 5). It is evident that the spectral density has a break on a scale of approximately 3000 km. The linear approximation ($\propto k^{-p}$), which was calculated separately for large and small scales, shows that the spectral indices vary significantly when moving from one region to another. This behavior suggests that turbulences are qualitatively different at different scales. The values of the exponent tend to –5/3 on scales up to 3000 km and to –3/2 on larger scales. Thus, the turbulent processes that can be described within the Kolmogorov model dominate on small scales, but there is anisotropy of turbulent processes on large scales owing to the nonzero mean magnetic field, and the turbulent processes resemble the Iroshnikov–Kraichnan pattern. Note that this result is consistent with the above results of the statistical analysis.

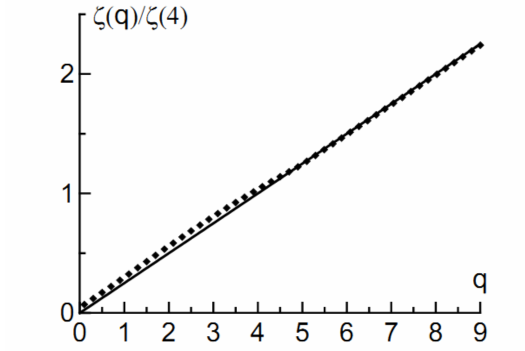

Figure 4: The ratio of the structural function of the qth order to the structural function of the fourth order: dots are the observations; the continuous line shows the model values calculated by the Iroshnikov–Kraichnan model.

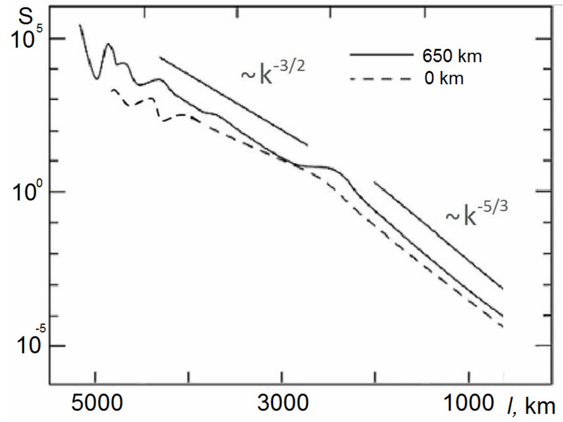

Figure 5: Spectral density S of the convective velocity field component for the active region of the photosphere.

Conclusions and discussion

The statistical and spectral analysis of the convective velocity field component found that:

– solar active regions exhibit two fundamentally different spectra of turbulence;
– the Kolmogorov type turbulent processes dominate on small scales, and the Iroshnikov–Kraichnan type turbulent processes are observed on large scales;
– the transition from the Kolmogorov spectrum to the Iroshnikov–Kraichnan spectrum takes place on a scale of approximately 3 Mm.

This scale corresponds to that of mesogranulation and is evidence of nonzero mean magnetic fields.

Moreover, it indicates the possibility of development of self-organized magnetic plasma structures (spots, bipolar groups, active regions, activity complexes, etc.).

It should be noted that this result is the first step towards finding the relationship between the mean magnetic field and the observed large scale solar magnetic structures. We emphasize that the modern concept of the solar mean turbulent magnetic field, which is commonly used in the dynamo theory, says nothing of structures, such as faculae and spots. Therefore, the discovery of the second turbulence spectrum with a nonzero mean magnetic field is essential to the further development of the theory and finding the relationship between the observed structures and the turbulent medium parameters.

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References

Benzi R., Ciliberto S., Tripiccione R. et al.: 1993, *Phys. Rev. E.*, **48,** 29.
Budaev V.P., Savin S.P., Zelenyi L.M.: 2011, *Usp. Fiz. Nauk*, **181**, 905.
Kolmogorov A.: 1941, *Dokl. Akad. Nauk SSSR*, **30**, 299.
Kostyk R.I., Khomenko E.V.: 2002, *Astron. Rep.*, **46**, 925.
Kozak L.V., Lui A.T.: 2008, *Kinematika Fiz. Nebesnykh Tel*, **24,** 72.
Kozak L.V., Savin S.P., Budaev V.P. et al.: 2012, *Geomagnetism and Aeronomy*, **52,** 445.
Kraichnan R.H.: 1965, *Phys. Fluids*, **8,** 575.
Novikov E.A. Stewart R.W.: 1964, *Izv. Akad. Nauk SSSR. Ser. Geofiz.,* **3**, 408.
Schroter E.H., Soltau D., Wiehr E.: 1985, *Vistas Astron.*, **28,** 519.
Stebbins R.T., Goode P.R.: 1987, *Solar. Phys.*, **110,** 237.