# Atmospheric Turbulence in the Clouds of Venus

Javier Peralta, Ricardo Hueso and Agustín Sánchez-Lavega

Grupo Ciencias Planetarias, Dpto. Física Aplicada I, Universidad del País Vasco
wubpecaj@bi.ehu.es

**Summary.** Power spectra obtained from cloud brightness distribution in Galileo violet images are used as a proxy of the kinetic energy power spectra in order to study the atmospheric turbulence in Venus. Interpretation based on a review of predicted regimes from classical laws is made, in addition to comparing Venus results with the ones obtained in Earth.

## 1 General Aspects about Turbulence

Turbulence is present in most fluids encountered in nature, from major oceanic currents to the terrestrial atmospheric boundary layer. It is not easy to define it precisely and does not allow a strict analytical study due to the inclusion of highly nonlinear terms in its equations. Between its main characteristics we can say that turbulent flows seem random and chaotic, have a rapid rate of diffusion of momentum and heat, as well as high levels of fluctuating vorticity translated in the existence of a big range of eddy sizes.

In general terms, we can characterize three-dimensional turbulence as a phenomenon in which *the kinetic energy is cascaded down from large to small eddies in a series of small steps until it is destroyed by viscous dissipation* [1]. The whole mechanism is usually characterized by a wavenumber spectrum called the Kinetic Energy Power Spectrum. We can associate a wavenumber $k$ with an eddy size $k^{-1}$, and the power function $E(k)$ represents the way energy is distributed as a function of $k$.

We can differentiate several regions of interest in the energy spectrum $E(k)$ attending to the relevant turbulent scales [2] as it can be seen in fig. 1. Let $L$ be the largest scale and $\eta$ the *Kolmogorov microscale*, at which viscous dissipation starts to become effective. The production of energy by the largest scales causes a peak of $E(k)$ at a certain $k \simeq L^{-1}$, and the dissipation of energy causes a sharp drop of $E(k)$ for $k > \eta^{-1}$. The range of wavenumbers with $k \gg L^{-1}$ as far as $k \simeq \eta^{-1}$ is usually called the *equilibrium range*, and the range for which $L^{-1} \ll k \ll \eta^{-1}$ is called the *inertial subrange*.

Kolmogorov [3] argued that for the *inertial subrange* $E(k)$ is independent of the viscosity but depends on the rate at which energy is dissipated by smaller scales. Being $\varepsilon$ the rate of dissipated energy, dimensional reasoning allows to formulate his famous *Kolmogorovs law*:

$$E(k) \propto \epsilon^{2/3} \cdot k^{-5/3} \tag{1}$$

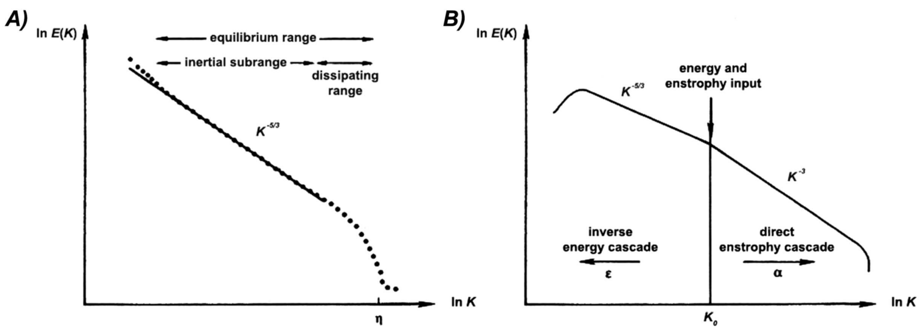


**Fig. 1.** Classical Power Spectra predicted by Kolmogorov for 3D isotropic turbulence (left) and by Kraichnan for 2D turbulence created by a random force (right).

The classical theory about turbulence was developed under the assumption of quasi-isotropic three-dimensional turbulence. Nevertheless, a peculiarity of large-scale turbulence when translated to the atmosphere fluid is that it is essentially two-dimensional in nature. Kraichnan [4] developed a theory for the case of two-dimensional turbulence created by a random force concentrated around a fairly large wavenumber that injected energy as well as enstrophy into the system, what its displayed in fig. 1. He demonstrated that in the absence of vortex stretching the nonlinear force will have the effect of transferring energy from large to small wavenumbers (instead of spreading symmetrically) and enstrophy propagating in the opposite direction. There are clearly two inertial regions in this case, characterized by the laws:

$$E(k) \propto \epsilon^{2/3} \cdot k^{-5/3} \qquad L^{-1} \ll k < k_0 \tag{2}$$

$$E(k) \propto \alpha^{2/3} \cdot k^{-3} \qquad k_0 < k \ll \eta^{-1} \tag{3}$$

where $\epsilon$ is the rate at which energy is injected into the system and $\alpha$ is the forward enstrophy flux to higher wavenumbers.

## 2 Turbulence in Planetary Atmospheres

Nastrom and Gage [5] obtained the very first energy power spectrum of turbulence from wind measurements taken from over 6900 commercial airplane flights from 1975 and 1979. In fig. 2 the spectrum for the zonal winds is displayed and we can distinguish two different regions with distinct slopes. On larger scales it shows approximately a $k^{-3}$ power-law over the synoptic scales and a clear $k^{-5/3}$ power-law behaviour for the mesoscale.

Some authors found "paradoxical" [6] that in the observed spectrum the $k^{-3}$ range appears for smaller wavenumbers than the $k^{-5/3}$ range, contrary to the predictions of Kraichnan. Gage and Nastrom [7] suggested that these ranges could be interpreted as Kraichnan's if there was an energy and enstrophy sink in the intermediate region, but this region is smooth and does not reflect the existence of a powerful dissipative force, in addition to the absence of candidate physical sinks.

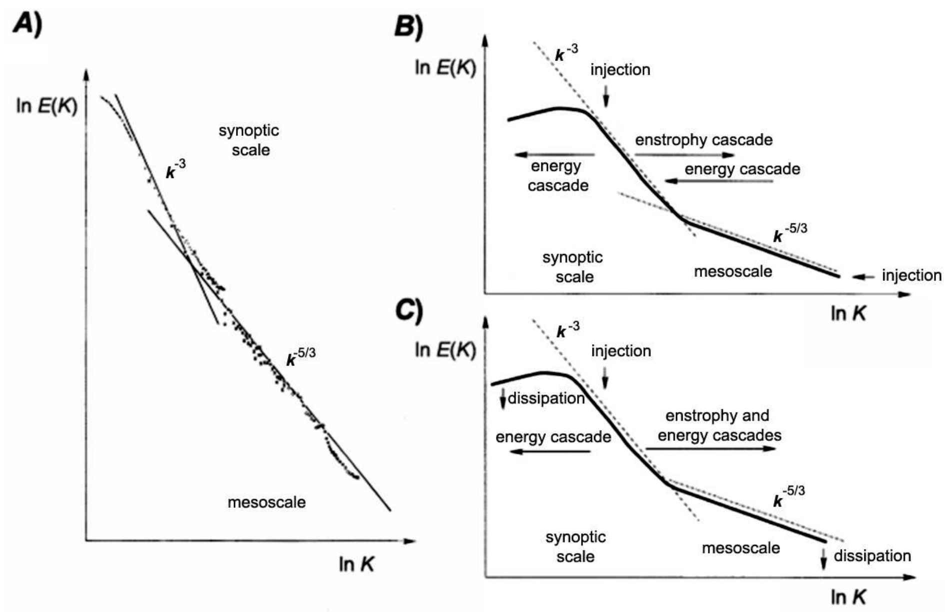


**Fig. 2.** Power Spectrum from zonal winds measured in the terrestrial atmosphere (A), and the same as interpreted by Lilly (B) [8] and Tung (C) [10].

As Kraichnan only considered the case with one force acting at fairly small scales [4], Lilly investigated the case with one large-scale force and one small-scale force [8]. He additionally argued that a combined energy and enstrophy inertial range in the intermediate region was possible, avoiding the need of a sink, as it is displayed in fig. 2. Nevertheless, numerical simulations of two-dimensional turbulence by Maltrud and Vallis with forcing at both ends of the spectrum produced a slope steeper than $k^{-3}$ and a transition region more abrupt than in atmospheric data [9]. Moreover, the "degree of universality" in spectral amplitude and shape encompassing both ranges for velocities and temperature [7] is hard to explain as a consequence of two unrelated forces at the two ends of the spectrum [10].

The hypothesis that the $k^{-5/3}$ range is the spectrum of two-dimensional turbulence with a negative energy flux has been seriously questioned since observational support for a direct energy cascade in the subsynoptic or mesoscales exist [11, 12]. Recently, Tung and Orlando [10] developed a two-level quasigeostrophic model that reproduces the entire Nastrom-Gage Energy Spectrum with forcing at only the large (synoptic) scales and dissipation at the small scales (i.e. viscous dissipation) as can be seen in fig. 2.

## 3 The Venus Case: data description and discussion.

In the case of Venus a retrieval of the energy power spectrum has not been feasible until now because typical errors in velocity determinations are of the same order as the wind speed turbulent fluctuation. Nevertheless, an indirect approach employing power spectra from the spatial cloud brightness distribution has been previously used and justified on Jupiter [13] and on Venus [14, 15, 16].

In a recent work [17] we carefully selected twenty violet images taken by SSI camera onboard Galileo spacecraft during its Venus flyby, and built longitude-latitude cylindrical projected maps covering as much longitude as possible. One of them is displayed in fig. 3, where many of the cloud features with different scales are possible manifestations of turbulent activity.

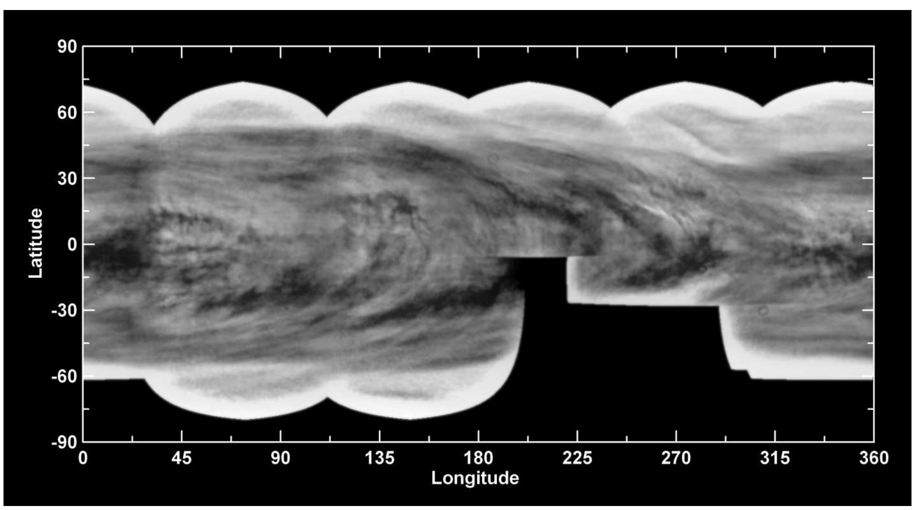


**Fig. 3.** Longitude-Latitude cylindrical projected map of the atmosphere of Venus built with up to 6 images from Galileo Violet images

Once zonal brightness scans were extracted from the cylindrical composites, the brightness power spectrum is estimated for each one and we finally logarithmically average over a certain number of them within a predetermined latitude band (see fig. 4).

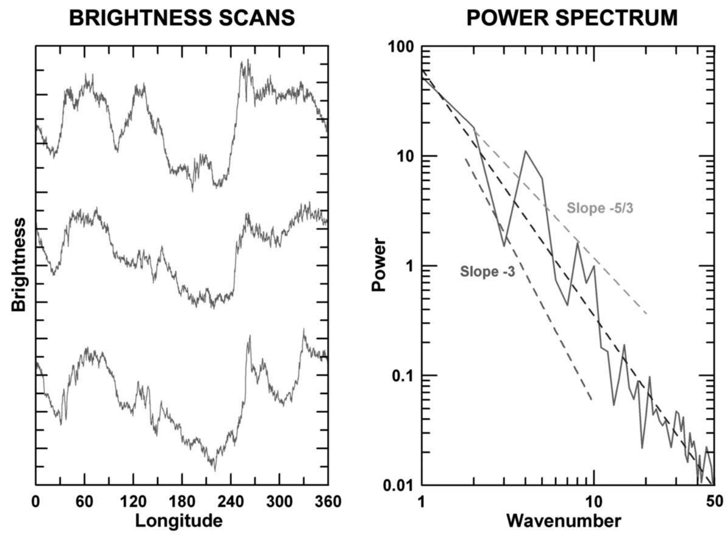


**Fig. 4.** Zonal Brightness Scans extracted from the cylindrical composite in fig. 3 (left) and Averaged Power Spectrum from zonal brightness scans within a latitude band of 10 centered in 20N (right). Slope between wavenumbers 1-50 is displayed in blue and compared with classical slopes.

It was interesting to note that the slopes resulting from the power spectra of the cloud brightness [17] are intermediate between those predicted by the classical turbulence theories for the kinetic energy spectra, i.e. $k^{-5/3}$ and $k^{-3}$ [3, 4], what could be indicating an intermediate regime between those described by the classical laws of turbulence. An energy spectrum described by a $k^{-2}$ law that resembles our results has been found on theoretical studies of two-dimensional turbulence [18], as well as recently in quasi-two-dimensional turbulent flows in laboratory experiments on rapidly rotating annulus fluids [19] supported by numerical simulations under similar conditions [20].

Our future research will focus on the theoretical interpretation of of the Venus's clouds brightness power spectrum using turbulence theories and numerical simulation.

*Acknowledgements:* This work has been funded by Spanish MEC AYA 2003-03216, with FEDER support and Grupos UPV 15946/2004. J.Peralta acknowledges an UPV fellowship and R.Hueso a "Ramón y Cajal" contract from MEC.

## References


1. L. Richardson: Weather Prediction by Numerical Process. Cambridge University Press (1922)
2. P.K. Kundu: Fluid Mechanics, Academic Press, Inc. (1990)
3. A.N. Kolmogorov: The Local Structure of Turbulence in Incompressible Viscous Fluid for very large Reynolds Numbers, (English translation, 1991). Proc.Roy.Soc.London **A434**, pp.9-13 (1941)
4. R.H. Kraichnan: Inertial Ranges in Two-Dimensional Turbulence. Physics Fluids, **10**, pp.1417-1423 (1967)
5. G.D. Nastrom, K.S. Gage, W.H. Jasperson: The atmospheric kinetic energy spectrum, 100-104 km. Nature, **310**, pp.36-38 (1984)
6. U. Frisch: Turbulence. Cambridge University Press (1995)
7. K.S. Gage, G.D. Nastrom: Theoretical Interpretation of Atmospheric Wavenumber Spectra of Wind and Temperature Observed by Commercial Aircraft During GASP. Journal of Atmospheric Sciences, **43**, pp.729-740 (1986)
8. D.K. Lilly: Two-Dimensional Turbulence Generated by Energy Sources at Two Scales, Journal of Atmospheric Sciences, **46**, pp.2026-2030 (1989)
9. M.E. Maltrud, G.K. Vallis: Energy spectra and coherent structures in forced two-dimensional and beta-plane turbulence. J.Fluid Mech., vol.**228**, pp.321-342 (1991)
10. K.K. Tung, W.W. Orlando: The $k^{-3}$ and $k^{-5/3}$ Energy Spectrum of Atmospheric Turbulence: Quasigeostrophic Two-Level Model Simulation. Journal of Atmospheric Sciences, **60**, pp.824-835 (2003)
11. S. Lambert: A diagnostic study of global energy and enstrophy fluxes spectra. Tellus, **33**, pp.411-414 (1981)
12. D.M. Straus, P. Ditlevsen: Two-dimensional turbulence properties of the ECMWF reanalyses. Tellus, **51A**, pp.749-772 (1999)
13. J. Harrington, T.E. Dowling, R.L. Baron,: Jupiters Tropospheric Thermal Emission. II.Power Spectrum Analysis and Wave Search. Icarus, **124**, pp.32-44
14. L.D. Travis: Nature of the atmospheric dynamics on Venus from power spectrum analysis of Mariner 10 images. Journal of Atmospheric Sciences, **35**, pp.1584-1595 (1978)
15. W.B. Rossow, A. Del Genio, S.S. Limaye and L.D. Travis,: Cloud morphology and motions from Pioneer Venus images. J.Geophys.Res.,**35**, pp.8107-8128 (1980)
16. A.D. Del Genio, W.B. Rossow: Temporal Variability of Ultraviolet Cloud Features in the Venus Stratosphere, Icarus, **51**, pp.391-415 (1982)
17. J. Peralta, R. Hueso, A. Sánchez-Lavega,: Cloud Brightness Distribution and Turbulence in Venus using Galileo Violet Images. *Submitted to Icarus* (2006)
18. R.T. Pierrehumbert: Tracer microstructure in the large-eddy dominated regime. Chaos Sol.Fractals, **4**, pp.1091-1100 (1994)
19. C.N. Baroud, B.B. Plapp, Z-S She, H.L.Swinney: Anomalous self-similarity in turbulent rapidly rotating fluid. Phys.Rev.Lett.,**88**, 114501-1 (2002)
20. P. Constantin: Energy Spectrum of Quasigeostrophic Turbulence. Phys.Rev.Lett.,**89**, 184501-1 (2002)