Chapter 9
Conclusions and Remarks

There are several famous quotes on turbulence which describe the difficulty to treat mathematically this problem but, the following two are particularly effective. While, on one hand, Richard Feynman used to say "Turbulence is the most important unsolved problem of classical physics." Horace Lamb, on the other hand, asserted "I am an old man now, and when I die and go to heaven there are two matters on which I hope for enlightenment. One is quantum electrodynamics, and the other is the turbulent motion of fluids. And about the former I am rather optimistic.".

We believe that also our readers, looking at the various problems that we briefly touched in this review, will realize how complex is the phenomenon of turbulence in general and, in particular, in the solar wind. More than four decades of observations and theoretical efforts have not yet been sufficient to fully understand how this natural and fascinating phenomenon really works in the solar wind.

We certainly are convinced that we cannot think of a single mechanism able to reproduce all the details we have directly observed since physical boundary conditions favor or inhibit different generation mechanisms, like for instance, velocity-shear or parametric decay, depending on where we are in the heliosphere. On the other hand, there are some aspects which we believe are at the basis of turbulence generation and evolution like: (a) we do need non-linear interactions to develop the observed Kolmogorov-like spectrum; (b) in order to have non-linear interactions we need to have inward modes and/or convected structures which the majority of the modes can interact with; (c) outward and inward modes can be generated by different mechanisms like velocity shear or parametric decay; (d) convected structures actively contribute to turbulent development of fluctuations and can be of solar origin or locally generated.

In particular, ecliptic observations have shown that what we call Alfvénic turbulence, mainly observed within high velocity streams, tends to evolve towards the more "standard" turbulence that we mainly observe within slow wind regions, i.e., a turbulence characterized by $e^+ \sim e^-$, an excess of magnetic energy, and a

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Kolmogorov-like spectral slope. Moreover, the presence of a well established "background" spectrum already at short heliocentric distances and the low Alfvénicity of the fluctuations suggest that within slow wind turbulence is mainly due to convected structures frozen in the wind which may well be the remnants of turbulent processes already acting within the first layers of the solar corona. In addition, velocity shear, whenever present, seems to have a relevant role in driving turbulence evolution in low-latitude solar wind.

Polar observations performed by Ulysses, combined with previous results in the ecliptic, finally allowed to get a comprehensive view of the Alfvénic turbulence evolution in the 3D heliosphere, inside 5 AU. However, polar observations, when compared with results obtained in the ecliptic, do not appear as a dramatic break. In other words, the polar evolution is similar to that in the ecliptic, although slower. This is a middle course between the two opposite views (a non-relaxing turbulence, due to the lack of velocity shear, or a quick evolving turbulence, due to the large relative amplitude of fluctuations) which were popular before the Ulysses mission. The process driving the evolution of polar turbulence still is an open question although parametric decay might play some role. As a matter of fact, simulations of non-linear development of the parametric instability for large-amplitude, broadband Alfvénic fluctuations have shown that the final state resembles values of σ_c not far from solar wind observations, in a state in which the initial Alfvénic correlation is partially preserved. As already observed in the ecliptic, polar Alfvénic turbulence appears characterized by a predominance of outward fluctuations and magnetic fluctuations. As regards the outward fluctuations, their dominant character extends to large distances from the Sun. At low solar activity, with the polar wind filling a large fraction of the heliosphere, the outward fluctuations should play a relevant role in the heliospheric physics. Relatively to the imbalance in favor of the magnetic energy, it does not appear to go beyond an asymptotic value. Several ways to alter the balance between kinetic and magnetic energy have been proposed (e.g., 2D processes, propagation in a non-uniform medium, and effect of magnetic structures, among others). However, convincing arguments to account for the existence of such a limit have not yet been given, although promising results from numerical simulations seem to be able to qualitatively reproduce the final imbalance in favor of the magnetic energy.

Definitely, the relatively recent adoption of numerical methods able to highlight scaling laws features hidden to the usual spectral methods, allowed to disclose a new and promising way to analyze turbulent interplanetary fluctuations. Interplanetary space is now looked at as a natural wind tunnel where scaling properties of the solar wind can be studied on scales of the order of (or larger than) 10^9 times laboratory scales.

Within this framework, intermittency represents an important topic in both theoretical and observational studies. Intermittency properties have been recovered via very promising models like the MHD shell models, and the nature of intermittent events has finally been disclosed thanks to new numerical techniques based on wavelet transforms. Moreover, similar techniques have allowed to tackle the problem of identify the spectral anisotropic scaling although no conclusive and final analyses have been reported so far. In addition, recent studies on intermittency of magnetic field and velocity vector fluctuations, together with analogous analyses on magnitude fluctuations, contributed to sketch a scenario in which propagating stochastic Alfvénic fluctuations and advected structures, possibly flux tubes embedded in the wind, represent the main ingredients of interplanetary turbulence. The varying predominance of one of the two species, waves or structures would make the observed turbulence more or less intermittent. However, the fact that we can make measurements just at one point of this natural wind tunnel represented by the solar wind does not allow us to discriminate temporal from spatial phenomena. As a consequence, we do not know whether these advected structures are somehow connected to the complicated topology observed at the Sun surface or can be considered as by-product of chaotic developing phenomena. Comparative studies based on the intermittency phenomenon within fast and slow wind during the wind expansion would suggest a solar origin for these structures which would form a sort of turbulent background frozen in the wind. As a matter of fact, intermittency in the solar wind is not limited to the dissipation range of the spectrum but abundantly extends orders of magnitude away from dissipative scales, possibly into the inertial range which can be identified taking into account all the possible caveats related to this problem and briefly reported in this review. This fact introduces serious differences between hydrodynamic turbulence and solar wind MHD turbulence, and the same "intermittency" assumes a different intrinsic meaning when observed in interplanetary turbulence. In practice, coherent structures observed in the wind are at odds with filaments or vortices observed in ordinary fluid turbulence since these last ones are dissipative structures continuously created and destroyed by turbulent motion.

Small-scale turbulence, namely observations of turbulent fluctuations at frequencies greater than say 0.1 Hz. revealed a rich and yet poorly understood physics, mainly related to the big problem of dissipation in a dissipationless plasma. Data analysis received a strong impulse from the Cluster spacecrafts, thus revealing a few number of well established and not contradictory observations, as the presence of a double spectral breaks. However, the interpretation of the presence of a power spectrum at small scales is not completely clear and a number of contradictory interpretations can be found in literature. Numerical simulations, based on Vlasov–Maxwell, gyrokinetic and PIC codes, have been made possible due to the increasingly power of computers. They indicated some possible interpretation of the high-frequency part of the turbulent spectrum, but unfortunately the interpretation is not unequivocal. The study of the high-frequency part of the turbulent spectrum is a rapidly growing field of research and, in this review mainly dedicated to MHD scales, the kinetic range of fluctuations has been only marginally treated.

As a final remark, we would like to point out that we tried to describe the turbulence in the solar wind from a particular point of view. We are aware that there are still several topics which we did not discuss in this review and we apologize for the lack of some aspects of the phenomenon at hand which can be of particular interest for some of the readers.