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Magnetic turbulence in and around the Earth's magnetosphere

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Abstract. Magnetic turbulence is found in most space plasmas, including the geospace environment. Recent spacecraft observations of magnetic turbulence in the ion foreshock, in the magnetosheath, in the polar cusp regions, and in the magnetotail will be reviewed. Turbulence features like the fluctuation level, the spectral power law index, the turbulence anisotropy and intermittency, and the turbulence driver will be addressed. The influence of such a turbulence on the plasma transport and dynamics will be described, also using the results of numerical simulations.

1 Introduction

Cosmic plasmas are organized in regions of fast flows, like the solar and stellar winds, and in regions where the magnetic field shapes the structure of the plasma, like coronal loops and the planetary magnetospheres. Fluctuations of velocity and magnetic fields are observed in most cases, due for instance to the interaction between flows of different speeds, or the interaction between flows and an obstacle like the magnetosphere. On the heliospheric scale, magnetic turbulence influences the propagation and acceleration of solar energetic particles and cosmic rays. On a more local, magnetospheric scale, understanding turbulence is important because it influences the transport of mass, momentum, and energy from the solar wind to the magnetosphere.

In the standard, hydrodynamic picture, fluctuation energy is injected at large scales, and nonlinear interactions lead to a cascade of energy from large to small scales, giving rise to a typical power-law turbulence spectrum. On the other hand, a large number of instabilities typical of plasmas, both at large scales and at microscales, can feed fluctuations into space plasmas, which then evolve into a power-law spectrum thanks to nonlinear interactions. Magnetic turbulence due to both phenomenologies is observed in and around the Earth's magnetosphere. Such a turbulence can be due either to velocity shear instabilities in the magnetosheath, or to magnetic reconnection at magnetic field reversals like the magnetopause and the magnetotail, or to kinetic instabilities due to particle beams and to the anisotropic distribution functions in the bow shock and in the magnetotail.

Many spacecraft have explored the near Earth space, yielding a rich set of magnetic field observations (e.g. Zimbardo, 2006). The International Heliophysical Year gives the opportunity to study these data in a coordinated, comparative way, and here we point out that similar analysis techniques can be used for different datasets. The observations point out the importance of the underlying nonlinear dynamics, but the many behaviours of plasmas and magnetofluids show that further studies are needed. Here we describe some stimulating, and often puzzling, observations, and indicate how the understanding of some problems can be advanced by the use of numerical simulations.

2 Turbulence in and around the magnetosphere

Relevant level of magnetic turbulence are observed in the solar wind, the ion foreshock, the magnetosheath, the polar cusps, the middle magnetotail, and the distant magnetotail. A statistical analysis of both plasma and magnetic turbulence in the magnetotail was carried out by Borovsky et al. (1997) on the basis of ISEE 2 data at about 20 R_E (Earth radii) downtail. They found that, averaging over several periods, the fractional variations of velocity, magnetic field, plasma density and temperature could be quantified as $\delta v/v \simeq 1$, $\delta B/B_0 \simeq 0.5$, $\delta n/n \simeq 0.2$ or less, and $\delta T/T \simeq 0.2$ or less. Also, the spectral index for velocity fluctuations ranged as $\alpha_v = 0.8-2$, while for magnetic fluc-

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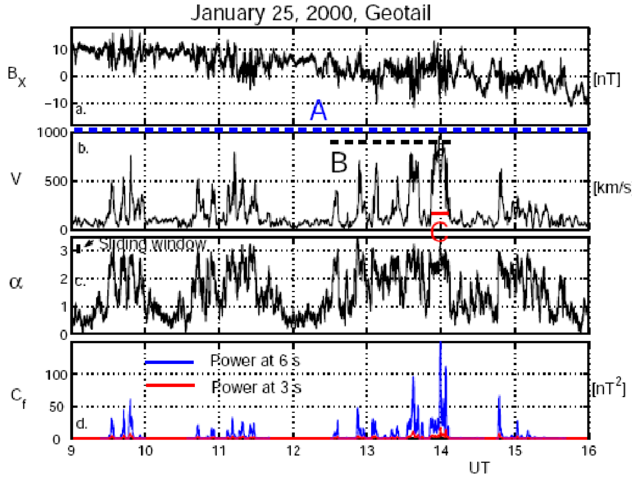

Fig. 1. Magnetic and velocity field measurements in the magnetotail, from Geotail spacecraft. **(a)** B_X component of the magnetic field; **(b)** bulk velocity; **(c)** scaling index α; **(d)** wavelet power on different time scales (adapted from Vörös et al. (2007a). © 2007 European Geosciences Union).

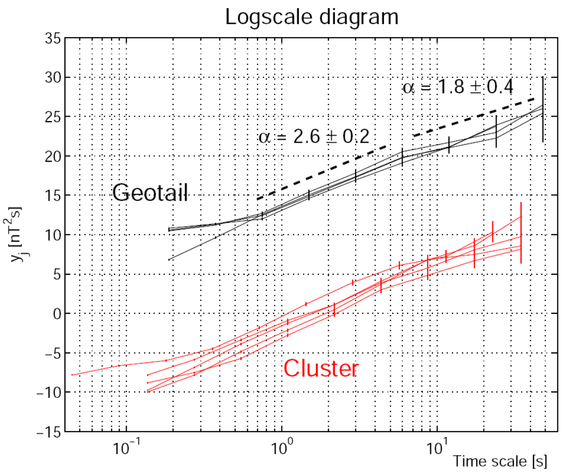

Fig. 2. Logscale diagrams computed from the magnitude of the magnetic field during 6 min long data intervals from Cluster and Geotail spacecraft (adapted from Vörös et al. (2007a). © 2007 European Geosciences Union)

tuations $\alpha = 1.6 - 3$. These features may be consistent with magnetohydrodynamic (MHD) turbulence, however magnetotail turbulence should be considered strongly driven, rather than fully developed, as is usually assumed for the solar wind (Borovsky et al., 1997).

Power law spectra in the middle tail, at about 25 R_E, were observed by AMPTE/IRM (Bauer et al., 1995). Turbulence is stronger in the central part of the plasma sheet, and power law spectra with spectral index $\alpha = 2 - 2.5$ are obtained, which are different from the Kolmogorov spectral index $\alpha = 5/3$ observed in the solar wind. Determining the value of the spectral index is important in order to understand what kind of nonlinear interactions are transferring energy from large to small scales. The magnetic turbulence level is $\delta B/B_0 = 0.2 - 0.8$, and it is stronger during disturbed periods, while there appear to be no difference between left and right polarizations. Magnetic turbulence in the distant tail, at about 100–200 R_E, has been observed by Geotail (Hoshino et al., 1994). This turbulence sometimes exhibits a kink power law spectrum, roughly coinciding with the wavelength expected for the most unstable modes of magnetic reconnection. These observations have stimulated the search for nonlinear evolution scenarios based on the percolation theory (Milovanov and Zimbardo, 2000).

However, recent detailed analysis of magnetotail turbulence, obtained from Geotail and Cluster spacecraft, see Fig. 1, shows evidence of an inertial range with slope close to 1.8, Fig. 2., that is very close to the Kolmogorov value of 5/3 (Vörös et al., 2007a). The magnetospheric physical conditions influence the measurement of spectral characteristic in geospace much more than in the solar wind, where the available range of scales is larger. For this reason, the estimation of spectral scalings in geospace has to be accompanied by a straightforward identification of the spatial and temporal structures of the driving processes. For example, magnetic and bulk speed data obtained from Geotail spacecraft (Fig. 1a and b) show non-stationary fluctuations and intermittent bursts of activity in the near-Earth plasma sheet. Obviously, high speed and low speed (down to ~ 0 km/s) intervals cannot be treated as a time series (like the intervals A and B in Fig. 1b) due to the failure of the Taylor frozen-in hypothesis. During interval C (around 14:00 UT in Fig. 1b) the bulk speed is relatively stable for some minutes and the small-scale spectral power is increased (Fig. 1d). The enhanced small-scale spectral power ensures that the energy of large-scale bulk flow de facto reaches the small scales.

During this time interval the bulk flow driven magnetic turbulence exhibits power law spectra with $\alpha \sim 2.5$ for frequencies higher than the ion gyrofrequency (assuming the validity of Taylor hypothesis in this case). Figure 1c shows the small-scale scaling index computed within sliding overlapping windows (Vörös et al., 2007a). For estimation of the large-scale scaling index (frequencies lower than the ion gyrofrequency), several minute long stationary data intervals have to be found with fluctuations present over multiple scales. However, stationary data intervals which are sufficiently long do not frequently occur in the Earth's magnetotail. Figure 2 shows the magnetic wavelet spectra of several 6 min long quasi-stationary intervals from Geotail (shifted for better visibility) and Cluster spacecraft. Time scales larger than a few seconds robustly exhibit power law scaling with scaling index $\alpha = 1.8 \pm 0.4$. Within measurement uncertainties this value indicates the presence of inertial energy cascade in

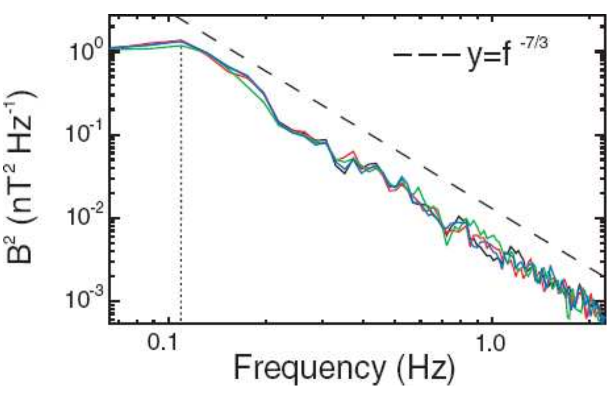

Fig. 3. Magnetic turbulence frequency spectra in the magnetosheath, as determined by the four Cluster spacecraft (from Sahraoui et al. (2006). © 2006 American Physical Society).

the magnetotail. It is worth mentioning that the analysis of non-stationary time intervals (e.g. intervals A, B in Fig. 1) leads to non-unique scaling index estimations, providing values between 1 and 3 in the Earth's magnetotail (Vörös et al., 2007a).

We assume that, under the assumption of homogeneous turbulence, isotropy and locality of interactions in wavenumber space, proper selection criteria for stationary multi-scale data intervals can be found in other regions of geospace, too. Close to boundaries, however, fluctuations exhibit anisotropies, therefore, universal scalings cannot be expected. It is known from laboratory experiments and numerical simulations that near boundaries α can change from 1.6 to 2.2 (e.g. Borovsky and Funsten, 2003). Using Cluster multipoint magnetic and plasma measurements it was possible to analyze the spatial structure of flow associated turbulence in the Earth's plasma sheet. It was found, that nonlocal interactions occur close to the boundaries of a plasma flow (Vörös et al., 2007b), therefore the fluctuations show non-universal statistics.

Turbulence is sometimes characterized by rare but intense fluctuations, which make up for magnetic field intermittency. Intermittent events correspond to a non-Gaussian, long tailed probability distribution of fluctuations δB around the average value. Magnetic turbulence in the solar wind is known to be intermittent (Sorriso-Valvo et al., 2001). The non Gaussian properties of magnetic turbulence in the magnetotail have been investigated by Vörös et al. (2003, 2004) and by Consolini et al. (2005). Non Gaussian distributions of fluctuations have been observed in the magnetotail after the current disruption associated with magnetospheric substorms, while before substorms the distributions are nearly Gaussian (Consolini et al., 2005). These observations emphasize that different turbulent features can be found in different periods, and that the magnetosphere is far from being a stationary system.

Up to now, Cluster remains the only space mission composed of 4 identical spacecraft flying together. This allows, under favourable conditions, to resolve spatial scales, as well as temporal variations. In the magnetosheath, with the 4 Cluster spacecraft one has turbulence power specra both in frequency, with $\alpha = 2.3$, see Fig. 3, and wavenumber, with $\alpha = 2.6$, see Fig. 4, (Sahraoui et al., 2006), while the spectrum does not change at the proton gyrofrequency $f_{cp} = 0.33$ Hz. A mirror instability driven by the temperature anisotropy is identified as the source of waves, and $\delta B/B_0 \simeq 0.4$. Temperature anisotropy in the magnetosheath is due to the compression of the shocked solar wind. Also, turbulence anisotropy in wavevector space is directly measured by Cluster (Sahraoui et al., 2006). We emphasize that turbulence anisotropy has a very direct influence on the magnetic field line structure, see below.

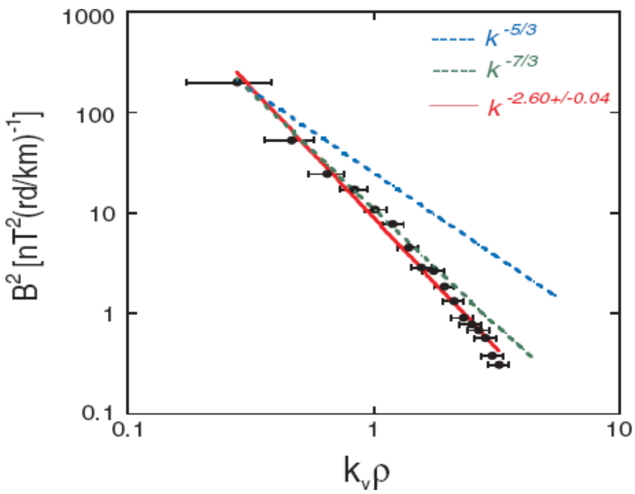

Fig. 4. Same as Fig. 3, but as a function of wavenumber (from Sahraoui et al. (2006). © 2006 American Physical Society).

Turbulence anisotropy is observed by Cluster in the ion foreshock region, too (Narita et al., 2006), and it is interesting to notice that in this case the spectral shape does not change at the proton gyrofrequency nor the proton inertial length, Fig. 5. This also shows that the wave-particle interactions in the foreshock regions can exhibit a variety of different behaviours (i.e. wave damping, wave energy transfer along the spectrum, or wave emission), and indeed emission of whistler waves accompanied by electron pitch angle diffusion can be found (e.g. Veltri and Zimbardo, 1993a,b). Whistler waves can also generate a turbulent cascade, which leads to a spectral slope of 7/3 when using the electron magnetohydrodynamics (EMHD) approach (Biskamp et al., 1996), while recently a slope of 11/3 was proposed within the framework of Hall MHD (Galtier and Buchlin, 2007). It interesting to notice that the latter slope is not too different from the slopes observed in the cusp and reported below in Figs. 6 and 7.

The analysis of wave modes in the magnetosheath has been performed by Sahraoui et al. (2003) by using the

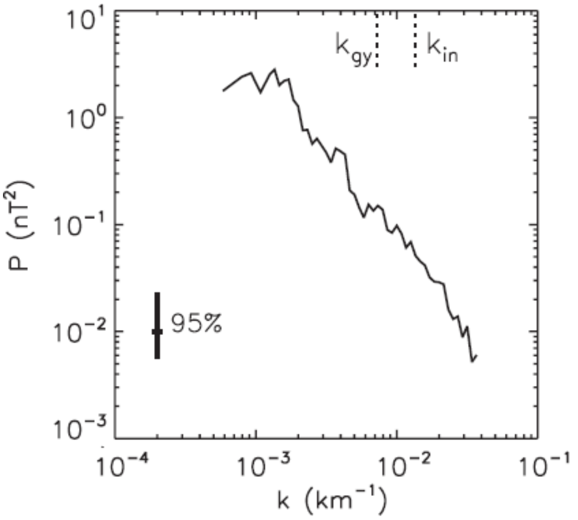

Fig. 5. Magnetic turbulence spectrum measured by Cluster in the ion foreshock, from Narita et al. (2006). The inverse of the ion gyroradius (inertial length) is indicated by k_{gy} (k_{in}). © 2006 American Physical Society.

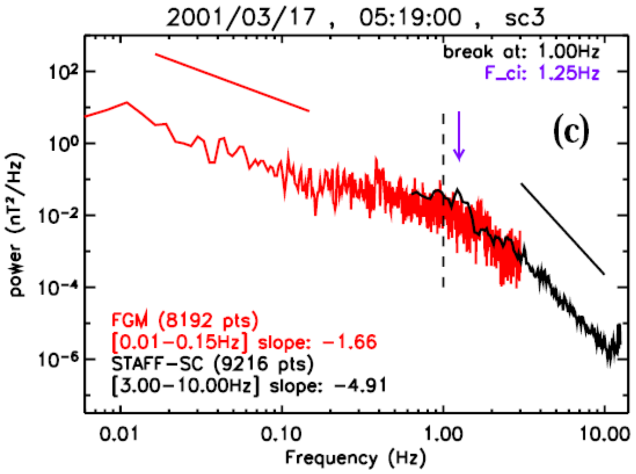

Fig. 6. Turbulence spectrum in the cusp region, from two Cluster instruments, the fluxgate magnetometer FGM (red line), and the wave instrument STAFF (black line). The proton gyrofrequency is indicated by the violet arrow. From Nykyri et al. (2006). © 2006 European Geosciences Union.

k-filtering technique applied to Cluster data. They compared the k-filtering results and the predictions of the linear theory. For the frequencies examined, the magnetic energy seems to be distributed over the low frequency modes: mirror, Alfven, and slow modes. Estimation of the Doppler shift shows that each frequency observed is a superposition of different frequencies in the plasma frame. This "mixture of modes" at a given observed frequency explains why the fluctuations are generally not observed to be polarized. On the other hand, understanding what are the dominant wave modes is of basic importance for understanding the turbulence dissipation processes which take place at the kinetic scales.

The four Cluster spacecraft can allow to study the correlations between magnetic field observations at different spacecraft, and this can help to identify the wave modes. Nykyri et al. (2003) have analysed high-resolution Cluster magnetic field data during three high-altitude cusp crossings. The Cluster separations for these crossings varied between 100 and 600 km. In the cusp, magnetic field fluctuations with clear peaks in power close to the local ion cyclotron frequency are detected, and both left- and right-handed polarisations, correspoding to Alfven and magnetosonic modes, respectively, are seen. There were no clear regions with just left- or right-handed waves, but the wave polarisations changed from one wave cycle to another. At large separations the power seen at different spacecraft can differ by orders of magnitude. For smaller separations, the power seen at the four spacecraft agrees better but still shows some differences. For all separations there was no significant correlation between the signals seen at different spacecraft, indicative of very local, possibly filamentary, structure (Nykyri et al., 2003).

Magnetic turbulence in the high altitude cusp, observed from Cluster spacecraft (Nykyri et al., 2006), shows a double slope spectrum, with a slope close to 1.2–1.7 below the proton gyrofrequency, and a slope close to 4.2–4.9 above the proton gyrofrequency, Fig. 6. This suggests that resonant dissipation, or at least a change in the turbulent cascade, happens around the proton gyrofrequency. This may correspond to the electron MHD ot the Hall MHD scenarios referred to above (Biskamp et al., 1996; Galtier and Buchlin, 2007). Yet, the same Cluster observations show that in other periods the slope at high frequency is smaller, of order 2.7–3.3, Fig. 7, suggesting that different dissipation scenarios can be going on. Indeed, the large-scale fluctuations observed by Cluster show some correlation between spacecraft but the higher frequency fluctuations show no correlation, indicating that the length scales of these waves are smaller than the spacecraft separation (500 km). In some cases, even emission spikes at the proton gyrofrequency are observed, Fig. 7, and sometimes, emission peaks are seen at several cyclotron harmonics (Nykyri et al., 2004; Cargill et al., 2005). In particular, Cargill et al. (2005) reports evidence of strong emission for at least four harmonics of the proton gyrofrequency at two of the four Cluster spacecraft, while the other two spacecraft sample a more regular spectrum without strong spikes. This shows that strong wave-particle interaction in the kinetic domain may be going on, and that this emission can be very localized in space. Both left- and right-hand polarised waves are found, with angles of propagation with respect to the ambient magnetic field that range from parallel to perpendicular (Nykyri et al., 2004; Cargill et al., 2005).

The variety of the observed spectral indexes show that

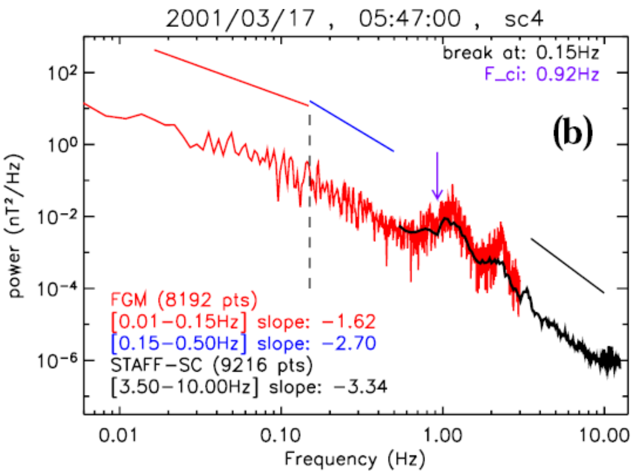

Fig. 7. Same as Fig. 6, but 28 min later. From Nykyri et al. (2006). © 2006 European Geosciences Union.

the nonlinear interactions in the magnetosphere are different both from those in ordinary fluids and from those in the solar wind, and show that more detailed investigations are needed.

3 Influence of magnetic turbulence

The importance of understanding magnetospheric turbulence is related to the influence that turbulence has on the transport of mass, momentum, and energy from the solar wind to the magnetosphere, and ultimately to ground level. Therefore, understanding turbulence in the heliosphere is one of the prime objectives of the International Heliophysical Year.

In the solar wind, the structure of a magnetic flux tube containing, for instance, solar energetic particles, is deformed by turbulence. Numerical simulations show that when the turbulence anisotropy is quasi-slab (i.e. wavevectors almost parallel to the background magnetic field) the flux tubes are deformed slowly, giving rise to an intermittent structure in the observations of energetic particles. On the other hand, when anisotropy is quasi-2D (i.e. wavevectors almost perpendicular to the background field) the flux tubes are deformed quickly, giving rise to a very fine, Gaussian-like structure in the observations of energetic particles (Zimbardo et al., 2004). Similar effects can be found in the magnetotail, so that time profiles of energetic particles can give information both on the magnetic field structure and on the acceleration mechanism. For instance, this is clearly seen in the observations of field aligned ion beamlets in the plasma sheet boundary layer (PSBL), coming from the distant X-line region. Indeed, recently Grigorenko et al. (2007), by analyzing Cluster data, have shown that the beamlet lifetime can be as long as 15 min, and that the observed beamlet duration of 1–2 min is not a temporal but rather a spatial effect. This is due to the variable magnetic connection of the spacecraft with the acceleration region. The "intermittent" magnetic connection is due to the fact that, because of magnetic turbulence, the magnetic flux tubes can acquire a distorted, and sometimes very convolute, spatial structure (Zimbardo et al., 2004); motions of the magnetotail cause the spacecraft to cross this structure and to sample an intermittent magnetic connection. It is interesting to notice that in this case the Alfven waves causing the distortion of magnetic flux tubes can be excited by a fire-hose instability due to the field-aligned ion beamlets themselves (Grigorenko et al., 2007). Alfven waves propagating along the magnetic field correspond to quasi-slab turbulence, and this agrees with the fact that structure 1–2 min long are observed. If the turblence would be quasi-2D, these structures would be much smaller than those corresponding to 1–2 min.

There are many influences of magnetic turbulence in magnetospheric dynamics, too. For instance, magnetospheric convection is based on the $\mathbf{E}\times\mathbf{B}$ drift, but a random magnetic field modifies the conventional picture. Adiabatic invariants, which are important for magnetotail dynamics and for study of magnetic reconnection, may be not conserved in a turbulent magnetic field. Test particle simulation of ion motion in magnetotail-like field reversal with turbulence have shown that turbulence can induce a double peak in the magnetotail current structure, in agreement with spacecraft observations (Veltri et al., 1998; Greco et al., 2002). Also, anomalous, i.e. superdiffusive, transport regimes can be found in the turbulent magnetotail (Zimbardo et al., 2000). Recent studies of ion transport across the magnetopause (Taktakishvili et al., 2007) have shown that the ion transport increases with the turbulence level, and that singly charged oxygen ions, of ionospheric origin, cross the magnetopause more easily than protons because of their large Larmor radius. In this sense, the magnetopause exhibits a selective permeability with respect to different ion species. Further numerical studies are needed to have a more comprehensive understanding of turbulent plasma trasport across the magnetopause, as well as of the role of magnetic turbulence in the ion energization.

4 Conclusions

We have illustrated some observed features of magnetic turbulence in and around the magnetosphere, that is in the magnetotail, in the magnetosheath, the ion foreshock, and the cusp, with the purpose of pointing out a number of unresolved issues. We discussed some numerical studies on the influence of turbulence on transport and heating. Magnetic turbulence appears to be a crucial ingredient for understanding the magnetospheric dynamics, and at a fundamental level, magnetic turbulence in the geospace environment represents a challenging nonlinear systems which needs to be understood.

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References

Bauer, T. M., Baumjohann, W., Treumann, R. A., Sckopke, N., and Luhr, H.: Low-frequency waves in the near-Earth's plasma sheet, J. Geophys. Res., 100, 9605–9617, 1995.

Biskamp, D., Schwarz, E., and Drake, J. F.: Two-dimensional electron magnetohydrodynamic turbulence, Phys. Rev. Lett., 76, 1264–1267, 1996.

Borovsky, J. E., Elphic, R. C., Funsten, H. O., and Thomsen, M.F.: The Earth's plasma sheet as a laboratory for flow turbulence in high-β MHD, J. Plasma Phys., 57, 1–34, 1997.

Borovsky, J. E. and Funsten, H. O.: MHD turbulence in the Earth's plasma sheet: Dynamics, dissipation and driving, J. Geophys. Res., 108, 1284–1321, 2003.

Cargill, P. J., Lavraud, B., Owen, C. J., Grison, B., Dunlop, M. W., Cornilleau-Wehrlin, N., Escoubet, C. P., Paschmann, G., Phan, T. D., Rezeau, L., Bogdanova, Y., and Nykyri, K.: Cluster at the Magnetospheric Cusps, Space Sci. Rev., 118, 321–366, 2005.

Consolini, G., Kretzschmar, M., Lui, A. T. Y., Zimbardo, G., and Macek, W. M.: On the magnetic field fluctuations during magnetospheric tail current disruption: A statistical approach, J. Geophys. Res., 110, A07202–A07214, 2005.

Galtier, S. and Buchlin, E.: Multiscale Hall-magnetohydrodynamic turbulence in the solar wind, Astrophys. J., 656, 560–566, 2007.

Greco, A., Taktakishvili, A. L., Zimbardo, G., Veltri, P., and Zelenyi, L. M.: Ion dynamics in the near Earth magnetotail: magnetic turbulence versus normal component of the average magnetic field, J. Geophys. Res., 107, 1267–1282, 2002.

Greco, A., Taktakishvili, A. L., Zimbardo, G., Veltri, P., Cimino, G., Zelenyi, L. M., and Lopez, R. E.: Ion transport and Lévy random walk across the magnetopause in the presence of magnetic turbulence, J. Geophys. Res., 108, 1395–1403, 2003.

Grigorenko, E. E., Sauvaud, J.-A., and Zelenyi, L. M.: Spatial-Temporal characteristics of ion beamlets in the plasma sheet boundary layer of magnetotail, J. Geophys. Res., 112, A05218, doi:10.1029/2006JA011986, 2007.

Hoshino, M., Nishida, A., Yamamoto, T., and Kokubun, S.: Turbulent magnetic field in the distant magnetotail: Bottom-up process of plasmoid formation?, Geophys. Res. Lett., 21, 2935–2938, 1994.

Milovanov, A. V. and Zimbardo, G., Percolation in sign-symmetric random fields: Topological aspects and numerical modeling, Phys. Rev., 62, 250–260, 2000.

Narita, Y., Glassmeier, K.-H., and Treumann, R. A.: Wave-number spectra and intermittency in the terrestrial foreshock region, Phys. Rev. Lett., 97, doi: 10.1103/PhysRevLett.97.191101, 2006.

Nykyri, K., Cargill, P. J., Lucek, E. A., Horbury, T. S., Balogh, A., Lavraud, B., Dandouras, I., and Reme, H.: Ion cyclotron waves in the high altitude cusp: CLUSTER observations at varying spacecraft separations, Geophys. Res. Lett., 30, 2263, doi:10.1029/2003GL018594, 2003.

Nykyri, K., Cargill, P. J., Lucek, E. A., Horbury, T. S., Lavraud, B., Balogh, A., Dunlop, M. W., Bogdanova, Y., Fazarkerley, A., Dandouras, I., and Reme, H.: Cluster observations of magnetic field fluctuations in the high-altitude cusp, Ann. Geophys., 22, 2413–2429, 2004.

Nykyri, K., Grison, B., Cargill, P., Lavraud, B., Lucek, E., Dandouras, I., Balogh, A., Cornilleau-Wehrlin, N., and Reme, H.: Origin of the turbulent spectra in the high-latitude cusp: Cluster spacecraft observations, Ann. Geophys., 24, 1–20, 2006.

Sahraoui, F., Pincon, J. L., Belmont, G., Rezeau, L., Cornilleau-Wehrlin, N., Robert, P., Mellul, L., Bosqued, J. M., Balogh, A., Canu, P., and Chanteur, G.: ULF wave identification in the magnetosheath: The k-filtering technique applied to Cluster II data, J. Geophys. Res., 108, 1335, doi:10.1029/2002JA009587, 2003.

Sahraoui, F., Belmont, G., Rezeau, L., Cornilleau-Wehrlin, N., Pincon, J. L., and Balogh, A.: Anisotropic turbulent spectra in the terrestrial magnetosheath as seen by the cluster spacecraft, Phys. Rev. Lett., 96, 075002, 2006.

Sorriso-Valvo, L., Carbone, V., Giuliani, P., Veltri, P., Bruno, R., Antoni, V., and Martines, E.: Intermittency in plasma turbulence, Planet. Space Sci., 49, 1193–1200, 2001.

Taktakishvili, A., Zimbardo, G., Amata, E., Savin, S., Greco, A., Veltri, P., and Lopez, R. E.: Ion escape from the high latitude magnetopause: analysis of oxygen and proton dynamics in magnetic turbulence, Ann. Geophys., 25, 1877–1885, 2007.

Veltri, P. and Zimbardo, G.: Electron whistler interaction at the Earth's bow shock. 1. Whistler instability, J. Geophys. Res., 98, 13 325–13 333, 1993a.

Veltri, P. and Zimbardo, G.: Electron whistler interaction at the Earth's bow shock. 2. Electron pitch-angle diffusion, J. Geophys. Res., 98, 13 335–13 346, 1993b.

Veltri, P., Zimbardo, G., Taktakishvili, A. L., and Zelenyi, L. M.: Effect of Magnetic Turbulence on the ion dynamics in the distant magnetotail, J. Geophys. Res., 103, 14 897–14 910, 1998.

Vörös, Z., Baumjohann, W., Nakamura, R., Runov, A., Zhang, T. L., Volwerk, M., Eichelberger, H. U., Balogh, A., Horbury, T. S., Glassmeier, K.-H., Klecker, B., and Reme, H.: Multi-scale magnetic field intermittence in the plasma sheet, Ann. Geophys., 21, 1955–1964, 2003.

Vörös, Z., Baumjohann, W., Nakamura, R., Runov, A., Volwerk, M., Zhang, T. L., and Balogh, A.: Wavelet analysis of magnetic turbulence in the Earth's plasma sheet, Phys. Plasmas, 11, 1333–1338, 2004.

Vörös, Z., Baumjohann, W., Nakamura, R., Runov, R. A., Volwerk, M., Asano, Y. Jankovicova, D., Lucek, E. A., and Reme, H.: Spectral scaling in the turbulent Earth's plasma sheet revisited, Nonlin. Proces. Geophys., 14, 535–541, 2007a.

Vörös, Z., Baumjohann, W., Nakamura, R., Runov, R. A., Volwerk, M., Takada, T., Lucek, E. A., and Reme, H.: Spatial structure of plasma flow associated turbulence in the Earth's plasma sheet, Ann. Geophys., 25, 13–17, 2007b.

Zimbardo, G.: Magnetic turbulence in space plasmas: in and around the Earth's magnetosphere, Plasma Phys. Control. Fusion, 48, B295, doi:10.1088/0741-3335/48/12B/S28, 2006.

Zimbardo, G., Greco, A., and Veltri, P.: Superballistic transport in tearing driven magnetic turbulence, Phys. Plasmas, 7, 1071–1074, 2000.

Zimbardo, G., Pommois, P., and Veltri, P.: Magnetic flux tube evolution in solar wind anisotropic magnetic turbulence, J. Geophys. Res., 109, A02113–A02123, 2004.