FINAL REPORT ON THE 4-WEEK PROGRAMME

GYROKINETICS IN LABORATORY AND ASTROPHYSICAL PLASMAS

(INI, 19 July – 13 August, 2010)

Organisers: W. Dorland *(Maryland)*, S. Nazarenko *(Warwick)*, A. Schekochihin *(Oxford)*

Motivation for the Programme. The physical motivation for the programme was the challenge of understanding plasma turbulence (and, more generically, kinetic turbulence). While the problem is long-standing, it is made particularly timely by a number of relatively recent developments: the start of the ITER project for fusion plasmas, unprecedented amount of data on small-scale plasma fluctuations becoming available through modern measurement techniques in the laboratory and in the solar wind, radical increase in computing power making fully resolved 3D kinetic simulations finally feasible, and substantial progress in understanding due to recent theoretical advances. Gyrokinetic theory has emerged as the theoretical framework of choice in both fusion plasmas and, increasingly, in space plasmas, as it offers a rigorous route to reducing the dimensionality of the kinetic phase space and the timescale range that must be handled by mind or computer. The gyrokinetic approximation (and, as has emerged during the Programme, especially the aspect of it that deals with the coupling between fluctuation scales and transport scales) does, however, pose a number of mathematical problems – ranging from nearly pure mathematical ones (well-posedness of the equations) to very practical (efficient numerical methods). The idea of the Programme was to address the problems of plasma turbulence, its numerical modelling and its gyrokinetic description by bringing together a very broad an interdisciplinary group of experts: from experimentalists and observers to numerical modellers, plasma theorists and applied mathematicians.

Programme structure, topics covered. During the first week (19-23 July 2010) a workshop was held, *"Kinetic-scale turbulence in laboratory and space plasmas: empirical constraints, fundamental concepts and unsolved problems,"* organised by S. Bale (Berkeley), T. Carter (UCLA), W. Dorland (Maryland), S. Nazarenko (Warwick), and A. Schekochihin (Oxford). A number of additional participants and invited speakers attended. The idea of the workshop was to set the stage by fixing the range of empirical facts and the challenges to modelling understanding that they pose.

In the three weeks that followed, the standard mode of operation was to hold two seminars a day: one in the morning and one after lunch. In addition, there were six special one-day or half-a-day workshops:

1. *Kinetic reconnection* (full day in week 2). Organisers: N. Loureiro (Lisbon), A. Schekochihin (Oxford), D. Uzdensky (Boulder). 26 July 2010
2. *Edge gyrokinetics* (half-day in week 2). Organiser: P. Catto (MIT). 27 July 2010
3. *Drift tearing and microtearing* (half-day in week 2). Organiser: N. Loureiro (Lisbon). 28 July 2010
4. *Gyrokinetics for simple laboratory plasma configurations* (full day in week 2). Organiser: P. Ricci (EPFL). 29 July 2010
5. *Gyrokinetic phase-space turbulence* (half-day in week 3). Organisers: J. Krommes (PPPL) & G. Plunk (Maryland). 2 Aug 2010

6. *Approaches to global full-f gyrokinetic simulations* (full day in week 4). Organiser: F. Parra (Oxford). 10 Aug 2010

The seminars, offline discussions and collaborations were structured around 11 working groups focused on specific problems:

1. *Alpha particles, their transport and Alfvenic instabilities* (moderator: I. Abel (Oxford))
2. *Astrophysical kinetics and gyrokinetics* (moderators: S. Balbus (ENS Paris) & G. Hammett (Princeton))
3. *Phase-space turbulence, energy flows in gyrokinetics* (moderators: J. Krommes (Princeton) & G. Plunk (Maryland))
4. *Edge gyrokinetics* (moderator: P. Catto (MIT))
5. *Global full-f simulations* (moderator: F. Parra (Oxford))
6. *Hamiltonian gyrokinetics* (moderator: A. Brizard (St Michael's College))
7. *Kinetic reconnection* (moderators: N. Loureiro (IST Lisbon) & D. Uzdensky (UC Boulder))
8. *Microtearing and high-beta gyrokinetics* (moderators: N. Loureiro (IST Lisbon) & C. Roach (CCFE))
9. *Sheared gyrokinetic turbulence, interactions between flows and turbulence* (moderators: F. Casson (Warwick) & E. Highcock (Oxford))
10. *Gyrokinetics for simple laboratory plasma configurations* (moderator: P. Ricci (EPF Lausanne))
11. *Tokamak transport* (moderator: M. Barnes (Oxford))

Further information: see http://www-thphys.physics.ox.ac.uk/research/plasma/ukgk.html.

Outcomes. The Programme outcomes are best summarised by the publications that were, in various degree, inspired by it. The list, supplied by the participants, is attached. These represent, in a sense, the "measurable outcomes." The less directly measurable but no less important ones are a new network of collaborations that have emerged (due to the interdisciplinary selection of the programme participants, for many this was the first time that they found each other attending the same scientific gathering) and the way in which the discussions held during the Programme have influenced the thinking of the community. It is perhaps symptomatic in less than year that has passed since the Programme, two other interdisciplinary events of this kind have been organised by the participants:

- "Dynamics and turbulent transport in plasmas and conducting fluids" (organised by N. Plihon et al. at Les Houches, February 28-March 11, 2011)
- "Vlasov-Maxwell kinetics: theory, simulations and observations in space plasmas" and "Fusion theory working group meeting" (organised by F. Califano and A. Schekochihin at Wolfgang Pauli Institute in Vienna, March 29-April 15, 2011)

While justice cannot be done within the space allocated to this Report to all the scientific discussions that took place during the Programme, the topics that received particular emphasis and so deserve special mention were

- Transport bifurcations in fusion plasmas and subcritically driven gyrokinetic turbulence
- Fast magnetic reconnection, plasmoid reconnection, gyrokinetic reconnection
- Momentum transport and energy conservation in gyrokinetic formalism and implications for numerical modelling

PUBLICATIONS

This is a list of papers (as supplied by the participants), both published and submitted, that were worked on/started/discussed/conceived/influenced/inspired by the discussions during the Programme.

Published

1. E. G. Highcock, M. Barnes, A. A. Schekochihin, F. I. Parra, C. M. Roach, and S. C. Cowley, "Transport bifurcation in a rotating tokamak plasma," Phys. Rev. Lett. 105, 215003 (2010)
2. S. A. Balbus and C. S. Reynolds, "Radiative and dynamic stability of a dilute plasma," Astrophys J. 720, L97 (2010)
3. D. A. Uzdensky, N. F. Loureiro, and A. A. Schekochihin, "Fast magnetic reconnection in the plasmoid-dominated regime," Phys. Rev. Lett. 105, 235002 (2010)
4. F. I. Parra, M. Barnes, E. G. Highcock, A. A. Schekochihin, and S. C. Cowley, "Momentum injection in tokamak plasmas and transitions to reduced transport," Phys. Rev. Lett. 106, 115004 (2011)
5. R. T. Wicks, T. S. Horbury, C. H. K. Chen, and A. A. Schekochihin, "Anisotropy of imbalanced Alfvenic turbulence in fast solar wind," Phys. Rev. Lett. 106, 045001 (2011)
6. F. I. Parra and I. Calvo, "Phase-space Lagrangian derivation of electrostatic gyrokinetics in general geometry", Plasma Phys. Control. Fusion 53, 045001 (2011)
7. P. J. Catto, G. Kagan, M. Landreman, and I. Pusztai, "A unified treatment of kinetic effects in a tokamak pedestal," Plasma Phys. Control. Fusion 53, 054004 (2011)
8. G. G. Plunk and T. Tatsuno, "Energy transfer and dual cascade in kinetic magnetized plasma turbulence," Phys. Rev. Lett. 106, 165003 (2011)
9. P. Ricci, C. Theiler, A. Fasoli, I. Furno, K. Gustafson, D. Iraji and J. Loizu, "Methodology for turbulence code validation: Quantification of simulation-experiment agreement and application to the TORPEX experiment," Phys. Plasmas 18, 032109 (2011)
10. A. Mishchenko and A. J. Brizard, "Higher-order energy-conserving gyrokinetic theory," Phys. Plasmas 18, 022305 (2011)

In press

11. C. H. K. Chen, A. Mallet, T. A. Yousef, A. A. Schekochihin, and T. S. Horbury, "Anisotropy of Alfvenic turbulence in the solar wind and numerical simulations," Mon. Not. R. Astron. Soc., in press (2011) [e-print arXiv:1009.0662]
12. F. I. Parra, M. Barnes, and A. G. Peeters, "Up-down symmetry of the turbulent transport of toroidal angular momentum in tokamaks," Phys. Plasmas, in press (2011) [e-print arXiv:1102.3717]
13. M. Opher, J. F. Drake, M. Swisdak, K. M. Schoeffler, J. D. Richardson, R. B. Decker, and G. Toth, "Is the magnetic field in the heliosheath laminar or a turbulent bath of bubbles?" Astrophys. J, in press (2011)

14. H. Che, J. F. Drake, and M. Swisdak, "A current filamentation mechanism for breaking magnetic field lines during reconnection," Nature, in press (2011)
15. J. A. Krommes, "The gyrokinetic description of microturbulence in magnetized plasmas," Annu. Rev. Fluid Mech 44, in press (2012)
16. F. Valentini, F. Califano, D. Perrone, F. Pegoraro, P. Veltri, "New ion-wave path in the energy cascade," Phys. Rev. Lett., in press (2011)
17. A. R. Field, C. Michael, R. J. Akers, J. Candy, G. Colyer, W. Guttenfelder, Y.-C. Ghim, C. M. Roach, S. Saarelma and the MAST Team, "Plasma rotation and transport in MAST spherical tokamak," Nucl. Fusion, in press (2011)
18. C. Theiler, I. Furno, A. Fasoli, P. Ricci, D. Iraji and B. Labit, "Blob motion and control in simple magnetized plasmas," Phys. Plasmas, in press (2011)

Submitted

19. F. I. Parra, M. Barnes, and P. J. Catto, "Sources of intrinsic rotation in the low flow ordering," Nucl. Fusion, submitted (2011) [e-print arXiv:1102.4613]
20. G. G. Howes, J. M. TenBarge, W. Dorland, E. Quataert, A. A. Schekochihin, R. Numata, and T. Tatsuno, "Gyrokinetic simulations of solar wind turbulence from ion to electron scales," Phys. Rev. Lett., submitted (2011) [e-print arXiv:1104.0877]
21. M. W. Kunz, "Dynamical stability of a thermally stratified intracluster medium with anisotropic momentum and heat transport," Mon. Not. R. Astron. Soc., submitted (2011) [e-print arXiv:1104.3595]
22. E. G. Highcock, M. Barnes, F. I. Parra, A. A. Schekochihin, C. M. Roach, and S. C. Cowley, "Transport bifurcation induced by sheared toroidal flow in tokamak plasmas," Phys. Plasmas, submitted (2011)
23. A. Zocco and A. A. Schekochihin, "Reduced fluid-kinetic equations for low-frequency dynamics, magnetic reconnection and electron heating in low-beta plasmas," Phys. Plasmas, submitted (2011) [e-print arXiv:1104.4622]
24. A. Mallet, A. A. Schekochihin, C. H. K. Chen, T. S. Horbury, R. T. Wicks, and T. A. Yousef, "Geometric and dynamic alignement in imbalanced Alfvénic turbulence," Phys. Rev. Lett., submitted (2011)
25. I. G. Abel, G. G. Plunk, E. Wang, M. Barnes, S. C. Cowley, W. Dorland, and A. A. Schekochihin, "Multiscale gyrokinetics for rotating tokamak plasmas. I. Fluctuations, transport and energy flows," Plasma Phys. Control. Fusion, submitted (2011)
26. J. Abiteboul, X. Garbet, V. Grandgirard, S.J. Allfrey, Ph. Ghendrih, G. Latu,Y. Sarazin, and A. Strugarek, "Conservation equations and calculation of mean flows in gyrokinetics," Phys. Plasmas, submitted (2011)
27. L. Schmitz, C. Holland, T. L. Rhodes, G. Wang, L. Zeng, A. E. White, J. C. Hillesheim, W. A. Peebles, S. Smith, R. Prater, G. R. McKee, W.M. Solomon, K. H. Burrell, C. Holcomb, E. J. Doyle, J. C. DeBoo, M. E. Austin, J. S. deGrassie, and C. C. Petty, "Reduced electron thermal transport in low collisionality H-mode plasmas in DIII-D and the importance of TEM/ETG-scale turbulence," Nucl. Fusion, submitted (2011)
28. C. Cremaschini, J. C. Miller, and M. Tessarotto, "Kinetic description of quasi-stationary axisymmetric collisionless accretion disk plasmas with arbitrary magnetic field configurations," submitted (2011) [e-print arXiv:1102.0179]