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Nonlinear processes in heliospheric plasma: models and observations

M. Velli[1], G. Einaudi[2], C. Chiuderi[1], P. L. Veltri[3], and the MM02242342 project team⋆

[1] Dipartimento di Astronomia e Scienza dello Spazio, Università di Firenze, Firenze, Italy
[2] Dipartimento di Fisica, Università di Pisa, Pisa, Italy
[3] Dipartimento di Fisica, Università della Calabria, Arcavacata di Rende, Italy

Abstract. We present the scientific objectives of the research project 'Nonlinear processes in heliospheric plasma: models and observations', co-financed by the Italian Ministry for Universities and Scientific Research, as well as a summary of some of the results obtained. The objective of the proposal was a detailed study of the nonlinear and dissipation-scale dynamics of heliospheric plasmas. The project focused on the study of wave propagation and properties of turbulence at the various scales, from the macroscopic scales of the solar wind, down to the microscopic scales of magnetic reconnection and turbulence dissipation, in its two aspects of evolutionary internal dynamics, and its effects on the transport of energetic particles of both heliospheric and extra-solar origins (cosmic rays, interstellar neutrals ionized in the solar wind as pickup ions).

Key words. magnetohydrodynamics – plasmas – solar wind – turbulence

1. Introduction

The study of nonlinear dynamics of magnetized fluids and plasmas is of crucial importance for the understanding of many astrophysical and geophysical phenomena, as well as for industrial applications such as controlled nuclear fusion devices. The solar wind offers us a unique opportunity to study such kind of processes, because it is a supersonic and superalfvenic plasma flow inside which satellite experiments have carried and continue to carry out extensive measurements which have furnished the scientific community with a wealth of data (velocity, magnetic field, plasma density, temperature etc. or also particle distribution functions) at a resolution which is not available in any Earth laboratory.

The plasma flow in the ecliptic plane is structured in high and low speed streams, the average wind speed increasing with heliomagnetic latitude, while the heliospheric

Send offprint requests to: M. Velli
⋆ R. Betta, P. Londrillo, F. Rappazzo, L. Del Zanna, S. Landi, F. Malara, V. Carbone, G. Zimbardo, L. Primavera, A. Greco, L. Sorriso-Valvo, P. Pommois, and F. Lepreti
Correspondence to: Dipartimento di Astronomia e Scienza dello Spazio, Università di Firenze, Largo Fermi 5, I-50125 Firenze, Italy

current sheet separating the global solar magnetic polarities is embedded within low speed streams. At high latitudes, the wind consists of a remarkably homogeneous (at least at solar minimum) flow with wind speed in the range 750-800 km s^{-1}, while the low speed wind flows at low latitudes with a speed of 300-400 km s^{-1} and is extremely variable. The high speed wind originates from the open magnetic field lines in the coronal holes, while the low speed streams must originate from field lines adjacent if not within the coronal activity belt (coronal streamers and active regions). It is clear that one should treat the chromosphere, transition region, corona and solar wind on an equal footing, and the question of coronal heating should be addressed within the constraints imposed on the energy deposition in the source regions by the characteristics observed in situ in the solar wind. In particular, it is now clear that the generation and the acceleration of solar wind cannot be related only to the high coronal temperature, but other local energy deposition mechanisms, like Alfvèn wave dissipation, are probably at work.

Data from space experiments also cover a very large range of spatial and temporal scales, corresponding to different physical processes, going from hydrodynamics and magnetohydrodynamics (large scales), to kinetic plasma physics (small scales). In many cases, due to different coupling mechanisms, such processes are related to one another, and all contribute to determine the complex phenomenology observed. Magnetic and velocity field fluctuations in the solar wind display the typical behavior of a developed turbulence where non linear effects play a major role in determining fluctuation properties. In some contexts, like slow speed streams, coherent structures at large scales are also recognized to be important in determining compressive features of the turbulence. Generation and properties of small scale coherent structures in the solar wind can be usefully studied, in the more general context of intermittency in fluids and MHD turbulence. The interaction of solar wind with the planetary magnetospheres gives rise to a wide phenomenology, detected by several space missions, which includes magnetic reconnection. The dynamics of magnetic reconnection, one of the main open problems in plasma physics, is probably dominated by kinetic effects, whose role needs to be more deeply understood, also in other situations like MHD shock dynamics and small scale turbulence. Finally, anomalous transport properties in a turbulent plasma can explain observations of high energy particles at high heliospheric latitudes by the Ulysses spacecraft. The strategy we adopted to tackle some of these questions was twofold: the development of high performance numerical codes on the one hand, the analysis of space and simulation data on the other hand. Because of the strong non linearity of the involved phenomena, progress in these fields must heavily rely on numerical simulations. The impossibility of performing controlled experiments in astrophysics is another factor contributing to the necessity of utilizing numerical simulations as proxies for real experiments. The development of numerical codes allows extensive and detailed numerical simulations of the dynamical evolution of plasmas in conditions as close as possible to the real ones. This implies the solution of the radiative fluid and magnetofluid equations as well as those describing collisionless or weakly collisional plasmas (i.e., Vlasov and Fokker-Plank equations). As a matter of fact, numerical simulations are nowadays more similar to laboratory experiments than to theoretical exercises. This is true in terms of planning efforts in the preparatory phase, of manpower required, of data analysis and cost. The data analysis concerned not only with the most recent space experiments (Ulysses, Geotail, Wind, SOHO) but also data from previous experiments (Isee, Helios, etc.), since there was and still is a lot of fundamental physics which can be better understood with a fresh look at such data. In this framework the importance of understanding the basic physical mechanisms which occur at sub-resolution scales and strongly influence the observed dynamics of the heliospheric plasma was a particular focus of our effort. In the following sections we describe some of the results obtained by our effort, divided into subsections concerning the various aspects of the dynamics.

2. Large scale magnetic and velocity shear instabilities

Shear flows in current sheets are typical of many coronal structures and are subject to both resistive instabilities and fluid instabilities. Such instabilities may play a fundamental role in the formation and acceleration of both the slow component of the solar wind, which seems to originate in the coronal streamer belt, and the fast component which seems to travel wherever open magnetic field lines are present. As part of this project we developed a model for the development and acceleration of magnetic islands in the current sheet embedded in the slow wind wake (Einaudi et al. 1991), and showed how the effects of compressibility of the plasma, melon seed force due to the spherical geometry effects and variation of Mach numbers due to solar wind expansion could all be included in a Cartesian simulation model periodic in the radial direction with appropriate characteristic boundary conditions in the transverse direction (Rappazzo et al. 2003). While the solar wind expansion tends to decrease the growth rate of the tearing/Kelvin-Helmholtz mode, the melon seed effect compensates so that the average acceleration of the slow dense plasma remains considerable. Applications of the physics of this kind of instability to wisps in the galactic center was presented in Dahlburg et al. (2002), while more general studies of the current-vortex sheet were presented in Antognetti et al. (2002). At present, the 2D code is being parallelized and generalized to 3D using the compact finite difference schemes already used.

3. Waves and turbulence in the solar atmosphere and solar wind

A number of different problems concerning the evolution of waves and turbulence, from the inner solar atmosphere outwards into the solar wind were investigated during this project. Numerical simulations in reduced MHD of the Parker field line tangling problem were carried out in 3D, and the results compared both to long-time simulations of a 2D magnetically forced analog system (Betta et al. 2001). Two important points were found. First of all, line-tying tends to inhibit the inverse cascade of the magnetic vector potential, slowing down but not stopping the formation of large-scale structures in the coronal field; second, because of the stabilising effect against tearing, line-tying allows for additional energy to be stored into the corona, therefore increasing the energy of bursts (which one would like to identify as nanoflares) which do occur. A final important point is that the coronal field may not be assumed to be a passive image of the photospheric footpoint motions. Once reconnection does occur, as it must in the low resistivity environment of the corona, the coronal field no longer resembles the photospheric velocity field, as is sometimes assumed in eddy-viscosity models of coronal heating.

To be able to reach much higher Reynolds numbers than with direct simulations, a shell model of MHD turbulence in planes perpendicular to the axial magnetic field was constructed and is being used to obtain statistical results on nano-flares. The shell models have shown to give statistics much closer to what is observed in real turbulent flows than SOC (Self-organized criticality) models, where the interaction leading to bursty behaviour is of the on-off type, and is driven passively by the external force (Lepreti et al. 2002; Carbone et al. 2002).

The problem of the evolution of turbulence with distance from the sun was approached in different ways, all invoking some role for compressible effects during the propagation outwards from the solar surface.

Much relevance was given to the role played by parametric instabilities, where an outwardly propagating Alfvén wave spectrum was shown to be unstable, leading in one dimension to the formation of a spectrum of inward waves saturating at a level close to that given by observations and showing a way out of the paradox of dynamic alignment operating in incompressible MHD (Malara et al. 2001). A study for a monochromatic wave-train in 2 and 3 dimensions using a novel high order shock capturing code showed how the waves develop fine-scales also in a direction perpendicular to the direction of propagation (Del Zanna et al. 2001), while the parametric decay phenomenon was shown to be robust also for arc-polarized modes, as observed in the solar wind (Del Zanna 2001). Progress on the heating due to wave propagation was made along two different fronts. On the one hand, the effects of phase deformation in chaotic magnetic fields, on the other, wave-wave couplings induced by propagation on x-type magnetic configurations was shown to lead to rapid formation of shock waves, which might have an important impact on the problem of particle acceleration in flares. From a more observational point of view, THEMIS observations of photospheric velocity and magnetic fields were used in a statistical analysis to sample turbulent photospheric fluctuations. The Proper Orthogonal Decomposition was used to distinguish granular convective structures from solar oscillations (Lepreti 2001; Berrilli et al. 2002). In the solar wind, statistical properties of MHD turbulence at various heliocentric distances were analyzed and its intermittency properties were described and compared with laboratory plasma turbulence (Bruno et al. 2001). Coherent structures at small scales responsible for the multi-fractal scaling laws were identified (Sorriso-Valvo et al. 2001; Kovàcs et al. 2001) and cancellation exponents were compared with those from numerical simulations (Sorriso-Valvo et al. 2002).

4. Anomalous transport and kinetic physics in the heliosphere

The small scale physics of the heliospheric plasma has profound effects via wave-particle interaction on the meso and large scale as particle acceleration and anomalous diffusion act to create the dissipative coefficients for the larger scales, changing the nature of the macroscopic closure equations, and yielding unexpected behaviours, for example of thermal conduction and heat flux in plasmas with large gradients, such as the solar transition region. Here, different particle-simulation techniques were used to describe the heat transport with non-Maxwellian distribution functions, such as K-functions, and their role in accelerating the solar wind. A full model including simplified radial dynamics but a Coulomb type collision operator was used both for the transition region and the solar wind (Landi & Pantellini 2001; Pantellini & Landi 2001), while a Monte-Carlo code was also developed to study the same problem (Greco & Veltri 2003, in preparation) and a comparison of the methods is in the works.

The strong nonlinearity of hydromagnetic turbulence in the heliosphere numerical simulations were used to evaluate diffusion coefficients in these situations where the usual assumptions of isotropy and quasi-linear theory clearly break down. A Monte-Carlo code was developed which evaluates transport taking into account large-scale heliospheric gradients, modeling the random terms as Wiener processes reproducing the previously evaluated diffusion coefficients. This code was used to explain the appearance at high latitudes of particles accelerated near the ecliptic in corotating interactions regions and associated shocks (Zimbardo et al. 2001a; Pommois et al. 2001a,b). The same code was used to study the propagation of high energy particles accelerated in solar flares to the Earth's magnetosphere (Zimbardo et al. 2001b) Transport in the Earth's magnetotail is also most-often characterized by anomalous diffusion, because of the strong fluctuating fields in the tail current sheets with oppositely directed fields. Outside the sheets, the level of fluctuations is much lower, leading to a low level of chaos in the fluctuations and random walks better described by Levy rather than Gaussian statistics. The statistical properties of the motion as a function of the amplitude of turbulence were studied in a numerical simulations of the tail including magnetic field fluctuations (Greco et al. 2001, 2002).

5. Conclusion

To conclude this brief summary of the research carried out by the 'Nonlinear processes in heliospheric plasma: models and observations' research teams in Pisa, Florence and Cosenza we would like to point out that a number of original numerical codes implementing various numerical methods have been developed, leading to a suite of tools capable of studying the nonlinear dynamics of astrophysical plasmas over a range of scales from the macroscopic, global dynamical ones, to the microscopic, kinetic scales where dissipation occurs. The international recognition of the work is demonstrated by participation with more than 58 invited or contributed talks in conferences over 2 years, as well as 44 papers in refereed journals. The research teams also acted as joint hosts for the international meeting Solar Wind 10, held in Pisa from June 17 to 21, 2002, and attended by 235 scientists from all over the world, demonstrating the vitality of nonlinear space plasma physics research in Italy and its recognition by the international community.

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