Proposal for an ISSI International Team – Call 2013

Superdiffusive transport in space plasmas and its influence on energetic particle acceleration and propagation

Gaetano Zimbardo (Team Leader, University of Calabria, Italy)
Horst Fichtner (Co-Leader, Ruhr University Bochum, Germany)

Abstract:

In the last few years it has been demonstrated, both by data analysis and by numerical simulations, that the transport of energetic particles in the presence of magnetic turbulence can be superdiffusive rather than normal diffusive (Gaussian). The term 'superdiffusive' refers to the mean square displacement of particle positions growing superlinearly with time, as compared to the normal linear growth. The so-called anomalous transport, which in general is comprising both subdiffusion and superdiffusion, has gained growing attention during the last two decades in many fields including laboratory plasma physics, but its serious appreciation in space physics is relatively recent.

With the proposed international team we intend to gather a number of experts on energetic particle transport, with a focus on what could be the main influence of superdiffusion on fundamental processes like diffusive shock acceleration (DSA) and solar energetic particle (SEP) propagation from the Sun to the Earth. Heliospheric, astrophysical, and laboratory plasmas will be considered, and both the theoretical approach and data analysis will be carried out.

1. Scientific rationale

1.1 Energetic particles in space plasmas

Various energetic particle populations are observed in the heliosphere: galactic cosmic rays (GCRs) entering from the interstellar medium nearly isotropically through the heliopause, termination shock particles and anomalous cosmic rays being accelerated at the solar wind termination shock and in the heliosheath [24,26], Jovian electrons originating in Jupiter's magnetosphere [4], solar energetic particles (SEPs) energized in the solar atmosphere and at traveling shocks driven by violent eruptions like flares and coronal mass ejections (CMEs) [3, 12]. Despite numerous measurements, many details of the relevant acceleration processes and of the related particle transport are not clarified yet [22]. The same applies, naturally, for particle acceleration and transport in astrophysical systems beyond the heliosphere: supernova remnants, which are thought to be the primary sources of GCRs [19, 2, 20], late-type massive and even solar-type stars [23, 13], galaxy clusters [31], and active galactic nuclei [16].

1.2 Anomalous transport in heliospherical, astrophysical, and laboratory plasmas

The most popular processes for acceleration and transport are the so-called first-order Fermi or diffusive shock acceleration (DSA) and Gaussian (or 'normal') spatial diffusion, respectively. While these processes have been employed successfully to explain many observations, there is an increasing number of measurements that cannot easily be explained by DSA and/or Gaussian diffusion. For instance, the largest shock to which we have direct access based on in situ observations, i.e., the solar wind termination shock, has recently been crossed by the Voyager spacecraft and, based on the observed compression ratio [24, 27], it is found that termination shock particles have a harder spectral index than that predicted by DSA. In addition, indications have been found that the transport of GCRs in the heliosphere can be anomalous, at least locally in time and space [17, 7, 31]. Similarly, the analysis of particle acceleration at traveling shocks, while showing broad agreement with DSA [5], also results in clear indications for anomalous and, in particular, superdiffusive transport [9, 11].

The term 'superdiffusive' refers to a mean square displacement growing superlinearly with time, as compared to the normal linear growth. Recently, many evidences of superdiffusion in the space environment have been found [18, 14, 9, 35, 15], and this is going to impact the observations of energetic particles. For instance, the measured SEP fluxes and energy spectra depend not only on properties of the source (e.g., the time evolution of CME-driven shock) but also on the propagation from there to the Earth, which could be superdiffusive, too [34]. Although SEP acceleration and transport are still unclear, many *in situ* observations are available from numerous instruments onboard spacecraft. This represents a unique opportunity for carrying out in-depth studies of particle transport in a magnetized turbulent plasma and for developing predictive capabilities for the arrival of high SEP fluxes in the near Earth space. To advance in this field, it is fundamental to investigate the relation between anisotropy and intermittency in solar wind turbulence, higher order moments for particle displacement, and anomalous transport.

Interpretation difficulties also exist for other astrophysical systems: models employing DSA struggle to produce particle spectra as flat as those inferred from radio observations of many old supernova remnants (energy spectral index $\gamma<2$) [30, 36]. Even more puzzling is particle acceleration in pulsar wind nebulae. The acceleration process is thought to occur at the highly relativistic shock that terminates the wind, where standard DSA cannot be at work [32]. In addition, the observed radio emission implies particle spectra are as flat as $\gamma=1$ over a broad energy interval, very difficult to obtain even with the alternative mechanisms proposed [1, 33]. It is noteworthy that superdiffusive transport can lead to energy spectral indices harder than those predicted by DSA [31, 10].

Very interestingly, anomalous transport also plays an important role in terrestrial and laboratory physical systems [28]. Regarding the latter, nuclear fusion experiments are important examples: the control of particle transport is perhaps the biggest physics problem to solve for attaining fusion in magnetically confined plasmas. Hence, great attention has been given to understanding transport in the corresponding laboratory plasma devices. Both anomalous regimes, i.e. sub- and superdiffusion, are found in such plasmas by a number of techniques [29, 6]. In parallel, it has been found, both by data analysis and by numerical simulations, that the transport of energetic particles in the presence of solar wind magnetic turbulence can be superdiffusive [18, 14, 9, 35, 15]. For these reasons, an exchange of ideas and techniques between the astrophysical and the fusion communities is crucial for advancing the understanding of, e.g., SEP propagation and for improving the magnetic confinement of plasmas. For instance, it would be important to investigate the correspondence between in situ measurements made by spacecraft and the full spatio-temporal coverage of the particle transport in the laboratory devices, as well as the role of particle orbit averaging effects versus turbulence eddy scale size.

1.3 Theoretical framework for the modeling of anomalous transport

The theoretical description of anomalous transport in the cases of both sub- and superdiffusion involves the use of a variety of tools like non-Gaussian statistics, Levy flights and walks, stochastic differential equations, long-range correlations, Hurst exponents, and fractional derivatives [8, 25, 11]. While these tools generally complement each other, they can result in differing predictions. Therefore, it is important to understand which tools are the most appropriate to describe energetic particle transport in space and laboratory plasmas, so that corresponding modeling results can constructively be confronted with measurements. In order to quantitatively compare the different methods, simple analytical reference cases have to be derived, while numerical solutions (using codes already available) of more complicated stochastic differential as well as fractional transport equations have to be computed and compared with each other.

2. Goals

In view of the scientific rationale the objectives of the ISSI team project are defined as follows:

(A) A review of the theoretical description of anomalous transport and an identification of the most appropriate framework for the quantitative modelling of superdiffusive transport of energetic particles in space and in laboratory plasmas.
(B) An identification of the most useful diagnostics to single out anomalous transport from *in situ* spacecraft data and from remote UV and X-ray data for supernova remnants.
(C) An investigation of the correspondence between time resolved (but local) measurements in a spacecraft frame and those obtained in a laboratory with full spatio-temporal coverage of particle interactions and, where possible, an exchange of conceptual frameworks and mathematical tools applied in space and laboratory physics.
(D) A quantitative assessment of the influence of superdiffusive transport on shock acceleration and propagation of energetic particles, using both theory and numerical modelling, and a clarification about what plasma turbulence conditions (i.e., fluctuation levels, anisotropies, intermittency) induce anomalous transport, and particularly superdiffusion.
(E) Applications to heliospheric and astrophysical data by assessing how superdiffusion can (a) influence the acceleration of solar energetic particles, (b) modify their arrival at the Earth, (c) influence the acceleration and propagation of termination shock particles, and (d) impact the interpretation of the observations of hard electron spectra at supernova remnants in terms of the new acceleration models.

The in-depth discussions during the two weeks at ISSI will provide the necessary guidelines for subsequent work at the home institutions. While at ISSI in Bern, we will contrast the various descriptions of superdiffusion to identify the one most appropriate for modeling energetic particle propagation; we will discuss analyses of heliospheric, astrophysical as well as laboratory data, and will define case studies of the heliospheric shock and supernova shocks in order to validate the methodology for extracting transport properties. Given the novelty of the proposed research, this will lead to cross-fertilization, to the publication of joint research papers, and possibly to the development of a new branch of research in space plasma physics.

3. Timeliness

The proposal is very timely because it has been found in recent years, both by data analysis and by numerical simulations, that the transport of energetic particles in the presence of solar wind magnetic turbulence or in laboratory plasma devices can be superdiffusive or subdiffusive rather than normal diffusive [18, 14, 29, 9, 7, 35, 6]. Furthermore, an extension of the anomalous transport paradigm to distant astrophysical objects like supernova remnants requires a solid development of the theory, to be achieved with the contribution of the experts on anomalous transport of the team. The results of the team will not only be useful for the interpretation of existing heliospheric spacecraft and UV and X-ray data, but also of those from the forthcoming missions Solar Orbiter and Solar Probe Plus, as these will allow to analyze energetic particle data close to the Sun, where different scalings of turbulence and particle mean free paths are expected to be found.

4. Importance and feasibility

The acceleration of cosmic rays is a long-standing problem in astrophysics which still lacks a full understanding. In this context, preliminary results on superdiffusive shock acceleration promise to explain a number of puzzling observations [31, 10]. High fluxes of SEPs are one of the major hazards of space weather, because their potential to damage and/or downgrade spacecraft operations. Therefore, understanding not only the acceleration but also the transport of SEPs, even outside the classical paradigm, has a high priority. Boosting the conceptual and methodological exchange between astrophysics, space physics, and laboratory plasma physics will lead to advanced physical insights and to a cross-fertilization of those fields.

The proposal is feasible because, on the one hand, the wealth of available heliospheric and astrophysical data allows us to perform the required data analysis. For instance, catalogues of shock crossings of the Ulysses and ACE spacecraft are as easily available [21; ACE catalogue at www.ssg.sr.unh.edu/mag/ace/ACElists/obs_list.html] as, e.g., supernova remnant catalogues [36]. On the other hand, the team leader is one of the main experts on superdiffusive transport in space plasmas, and the expertise of the team members covers in-depth data analysis, the theory of anomalous transport, and extended analytical as well as numerical modelling: this will allow the team to address the objectives defined above.

5. Expected output

The team will establish anomalous transport of energetic particles as an important regime in space plasmas, and will develop the methodologies to extract anomalous transport properties from data analysis: these are considered to be major breakthroughs. The latter will be matched by modern as well as novel numerical methods to solve the corresponding transport equation(s) of energetic particles for the case of superdiffusion. The team will jointly publish papers on data analysis as well as the results of numerical modeling of superdiffusion in heliospheric, interstellar, and laboratory scenarios and will summarize the present knowledge in a review. Results on specific heliospheric and astrophysical case studies will be presented at international conferences.

6. Added value from ISSI for the implementation of the project

In the proposed team we gather experts (i) on the solar wind dynamics including turbulence and large-scale traveling structures like coronal mass ejections, (ii) on SEP transport, collisionless shock physics, galactic cosmic rays and supernova remnants, and (iii) on the theoretical and experimental description of anomalous transport, and in particular superdiffusion, in laboratory and space plasmas. The informal atmosphere of an ISSI team and the limited number of participants are ideal for brainstorming and a subsequent assessment as well as comparison of ideas and differing points of view, thereby providing cross-fertilization and guidelines for future research. We notice that those diverse expertises cannot easily be gathered at usual conferences: therefore, the proposed ISSI team represents a unique chance to bring together different specialists.

7. List of confirmed members

Elena Amato (Oss. Astrofis. Arcetri, INAF, Italy)
Silvia Dalla (University of Central Lancashire, UK)
Ambrogio Fasoli (Center for Research in Plasma Physics, EPFL, Switzerland)
Horst Fichtner (Co-Leader, Ruhr University Bochum, Germany)
Ivo Furno (Center for Research in Plasma Physics, EPFL, Switzerland)
Joe Giacalone (University of Arizona, Tucson, USA)
Kobus le Roux (CSPAR, University of Alabama, Huntsville, USA)
Silvia Perri (University of Calabria, Cosenza, Italy)
Andreas Shalchi (University of Manitoba, Winnipeg, Canada)
Rami Vainio (University of Helsinki, Finland)
Aleksander Weron (Wroclaw University of Technology, Poland)
Gaetano Zimbardo (Team Leader, University of Calabria, Cosenza, Italy)

8. Schedule of the project

We plan to have two one-week meetings at ISSI, gathering about 12 researchers. Due to ongoing commitments, the first meeting is planned for January 2014, and the second meeting for July 2014 (the exact dates to be fixed after approval of the proposal). A few (self-funded) experts may potentially be added. The first meeting will be dedicated to discussions of the theory and establishing the methodology for data analyses. The period in between the meetings will be used for more extensive data analysis, numerical simulations, and for writing first drafts of papers. The second meeting will be used to consolidate the results of the data analyses and the numerical simulations, and to finalize the papers, which will be submitted shortly thereafter.

9. Required facilities

We require standard ISSI facilities: one meeting room with a beamer, internet connections, the possibility to print a limited number of paper sheets, access to the library and access to coffee/tea break facilities.

10. Financial support

We require standard ISSI financial support (accomodation, per-diem) for two one-week meetings for 12 team members plus 1-2 young scientists. Funding to cover travel costs is under the responsibility of the team members (except for the team leader).

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Address, telephone, fax, e-mail of participants:

1. Gaetano Zimbardo (Team Leader)
Dipartimento di Fisica, Universita' della Calabria
Ponte P. Bucci, Cubo 31C
87036 Rende (CS), Italy
Phone: +39-0984-496134
Fax: +39-0984-494401
e-mail: gaetano.zimbardo@fis.unical.it

2. Elena Amato
INAF - Osservatorio Astrofisico di Arcetri
Largo E. Fermi, 5
50125 Firenze - Italy
Phone: +39 055 2752 236
Fax: +39 055 220039
e-mail: amato@arcetri.astro.it

3. Silvia Dalla
Jeremiah Horrocks Institute, CEPS
University of Central Lancashire
Preston PR1 2HE, UK
Tel: +44-1772-893527
Fax: +44-1772-892996
Email: sdalla@uclan.ac.uk

4. Ambrogio Fasoli
Executive Director
Centre de Recherches en Physique des Plasmas
Association EURATOM - Confédération Suisse
Ecole Polytechnique Fédérale, Station 13
CH-1015 Lausanne, Switzerland
Tel.: +41 - (0)21 - 693 34 92 (direct) or 34 87 (secr.)
Fax: +41 - (0)21 - 693 51 76
e-mail: ambrogio.fasoli@epfl.ch

5. Horst Fichtner (Co-Leader)
Institut fuer Theoretische Physik
Lehrstuhl IV: Weltraum- und Astrophysik
Ruhr-Universitaet Bochum
D-44780 Bochum, Germany
E-Mail : hf@tp4.rub.de
Fax : (49) 234--32-14177
Phone : (49) 234--32-23786
Web : http://www.tp4.rub.de/~wwwhelio/en/

6. Ivo Furno
Center for Research in Plasma Physics (CRPP)
Ecole Polytechnique Federale de Lausanne (EPFL)
Association Euratom-Suisse,
CH-1015 Lausanne, Switzerland
Tel.: +41 - (0)21 - 693 34 94
Fax: +41 - (0)21 - 693 51 76
E-mail: ivo.furno@epfl.ch
Website: http://crpp.epfl.ch/

7. Joe Giacalone
Department of Planetary Sciences
University of Arizona
Tucson, AZ 85721-0092 (USA)
Tel: (520) 626-8365
Fax: (520) 626-8250
e-mail: giacalon@lpl.arizona.edu

8. Jakobus A. le Roux
Department of Physics & Center for Space Plasma and Aeronomic Research,
University of Alabama in Huntsville,
Huntsville, AL, 35899 (USA)
Phone: 256.961.7321
Fax: 256.961.7403
e-mail: jar0013@uah.edu

9. Silvia Perri
Dipartimento di Fisica
Universita' della Calabria
Ponte P. Bucci, Cubo 31C
I-87036, Rende, Italy
Tel: +39-0984-49-6130
Fax: +39-0984-49-4401
E-mail: silvia.perri@fis.unical.it

10. Andreas Shalchi
Department of Physics & Astronomy
University of Manitoba
301 Allen Building
Winnipeg, Manitoba
Canada R3T 2N2
Telephone: (204) 474-9874
Fax: (204) 474-9855
Email: shalchi@physics.umanitoba.ca

11. Rami Vainio
Department of Physics
P.O.Box 64
FI-00014 University of Helsinki
Finland
tel. +358-9-19150676
fax: +358-9-19150610
email: rami.vainio@helsinki.fi

12. Aleksander Weron
WUT - Wroclaw University of Technology,
Institute of Mathematics and Computer Science,
Wyspianskiego 27,
50-370 Wroclaw, Poland
Tel. +48-71 320-3101,
mobile:+48 607 821030
Fax. +48-71 320-2654,
E-mail: aleksander.weron@pwr.wroc.pl,
www.im.pwr.wroc.pl/~weron