Magnetic Helicity in Astrophysical Plasmas

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Proposal to ISSI Bern for an International Team in Space Sciences

Abstract

Magnetic helicity is a general measure of the twist and mutual linking of magnetic field lines that has recently received wide attention from different areas of Astrophysics. We propose an International Team formed by experts in magnetic helicity studies from different disciplines, such as stellar dynamos, solar corona and coronal mass ejections, magnetic turbulence and reconnection, both in theoretical models as well as in numerical simulations and solar observations. The main objective of the International Team is to bring helicity estimation methods that were developed in different fields under the same theoretical framework, so that they can be meaningfully compared with each other, and quantitatively benchmarked. In particular, we will consider helicity computations based on spectral methods applied to periodic domains (as used in free decaying turbulence and solar wind studies) and non-periodical domains (more typical of low-corona solar applications), and compare them with the finite-volume and flux-injection methods typically used in magneto-hydrodynamical simulations as well as in solar observations. Novel methods applying helicity estimations to individual field lines and their application to volume-filling fields will be also included. The comparison between different methods will be performed using numerical simulations as controlled test-cases to provide quantitative benchmarking and clear indications of the methods' limitations and assumptions. Their application to observed solar data, on the other hand, will allow to confront such methods with the additional complexity of real observations.

Scientific Rationale

Most astrophysical objects are recognized to be heavily influenced by the properties and evolution of omnipresent magnetic fields. The evolution of stars and their influence on the immediate neighborhoods, the interaction between stellar coronae and planetary magnetospheres of some planets, not least for their critical role in creating an environment suitable to life, down to the threats that solar eruptions pose to our increasingly technology-dependent societies, are but few examples of the importance of magnetic fields in space sciences. For this reason, an always increasing attention is being devoted to understand how magnetic fields are generated by dynamo processes in stars, how they surface shaping the stellar coronae, how they generate instabilities producing coronal mass ejections, and eventually interact with magnetospheres, in particular of Earth, in what is meanwhile known as space weather.

One of the most promising conceptual tools that has received wide attention in recent years in different research areas is magnetic helicity. Magnetic helicity is a general measure of the entanglement of magnetic fields, that concisely expresses the amount of twist and mutual winding of field lines in a given configuration. The appeal of helicity largely comes from being a conserved quantity [Moffatt 1969, Berger 1984] in typical solar and stellar conditions, which makes it a suitable tracer of magnetic field during its transformations from the interior of stars to near-planetary environments. The advances in the theory of magnetic helicity of the recent years are largely the result of its gauge-invariant formulation known as *relative magnetic helicity* [Berger & Fields 1984, Finn & Antonsen 1985]. This gauge-independent definition allows for method-independent estimations of helicity in generic spatial domains, which, in turn, has open the possibility of applications to natural astrophysical plasmas.

However, magnetic helicity is a nontrivial conceptual tool, and a very sensitive one in applications. Therefore, the rather extensive literature of the last three decades has produced a variety of methods that are only partially consistent with each other, and very often tightly tailored to the particular application they were devised for. Hence, the overarching goal of the proposed International Team is

to reorder the current understanding of magnetic helicity methodologies from different fields of space physics, and to benchmark them using a representative combination of numerical simulations and observations.

In this respect, the Sun offers the opportunity of spatially-resolved observations for testing general models and theories that find application in different branches of plasma physics and astrophysics. We intend to pursue that goal through the following series of focused objectives:

Objective 1: **Quantitative assessment of the effect of boundary conditions, and comparison of finite boundaries versus infinite/spherical boundaries**.
Finite-volume methods compute the magnetic helicity from a known magnetic field in a given rectangular volume [Valori *et. al* 2016], whereas flux-injection methods compute the helicity from the flux through its boundaries [Pariat *et al.* 2005, Liu *et al.* 2012]. The comparison between finite-volume and flux-injection methods directly addresses the problem of helicity conservation, as treated by [Pariat *et. al* 2015], but also of the role of boundary conditions in the derivation of the specifically employed helicity formulae. This is particularly important in the solar case, where the magnetic field is measured practically at one boundary only, namely at the photosphere. More generally, in applications to observed physical systems, boundaries have a finite extension, and formulae derived for infinite boundaries, or spherical geometries, do not necessarily apply to finite volumes. The comparison between finite-volume and flux-injection methods was partially addressed by a previous ISSI International Team[1], but we extend here that testing to spherical geometries and to spectral methods (see also Objective 3).

Objective 2: **Comparison of field-line and finite-volume helicities in volume-filling models of the coronal magnetic field.**
Finite-volume methods have been recently complemented by the computation of the helicity associated to individual field lines [Yeates *et al.* 2011, Russell *et al.* 2015], which is of particular interest for applications to reconnecting field lines, *i.e.* to changes of the topology of the magnetic field. Gauge-invariant formulations of such methods are being developed, and this is therefore a perfect time to test them. To that purpose, we will exploit

[1] International Team on *Magnetic Helicity estimations in models and observations of the solar magnetic field (*2014-2016) http://www.issibern.ch/teams/magnetichelicity/index.html
See also the IT final report

the fact that finite-volume and field-line helicity methods are supposed to converge to the same helicity value when applied to volume-filling fields, such as the solar atmosphere above an active region. Additionally, considering the recent advances in the preparation of observation from the *Solar Dynamic Observatory* that can be used as boundary conditions for such models [Liu *et al.* 2017], we are now in the perfect time to apply such methods to global solar field [Yeates *et. al* 2016] based on observed photospheric values.

Objective 3: Comparison of magnetic helicity estimations using spectral and finite-volume methods in numerical simulations.

An entirely different line of research, more specific to turbulence and dynamo studies, is the spectral characterization of the helicity [Frisch 1975, Müller and Malapaka 2013]. The fundamental scaling laws of magnetic field generation are typically studied using spectral tools that associate turbulent motion and the induction equation for the evolution of the large-scale magnetic field in numerical simulations. The fundamental character of such studies often requires simplifying assumptions concerning the spatial and temporal properties of the turbulent motion, and the effect of the finite character of the considered physical volumes on helicity is often neglected. Similarly, specific gauges have been developed for numerical simulations [Mitra *et al.* 2010, Candelaresi *et al.* 2012]. A task of the International Team in this respect is to study the relation between boundary conditions and assumptions in spectral methods applied to finite-volume numerical simulations, and how such results compare to the relative magnetic helicity values as computed from finite-volume and flux-injection methods [Mitra *et al.* 2009].

Objective 4: Comparison of magnetic helicity estimations using spectral and finite-volume methods in observations.

The photosphere is the connecting layer between the sub-surface dynamo generating the magnetic field and the coronal atmosphere, source of space-weather-relevant activity. In the case of the Sun, the photosphere is resolved at impressively high resolutions, which allows to study the connecting layer between dynamo and corona in details. As testing grounds for more general stellar dynamo models, applications to the solar case can provide crucial information indeed. In particular, very recently, a multi-scale spectral method for detection of spectral bimodality in observations of the solar photosphere was devised [Brandenburg *et al.* 2017]. Such applications offer a natural *trait d'union* between helicity estimation methods in solar dynamos and in coronal studies. Specific tests will be designed to prove the validity of such multi-scale methods using numerical simulations in spherical domains. Additionally, the spectral (multi-scale) analysis of specific solar observations will be compared with the integral methods described above (finite-volume, flux-injection, field-line-helicity).

In conclusion, the above series of studies will allow the International Team to test methods of helicity estimations in turbulent or laminar plasmas, methods that are based on spectral or integral approaches, and that are specifically developed for dynamo or coronal helicity studies. A number of numerical simulations and observations will be employed as tests fields for comparing results from different methods. A quick exploration of the recent publications shows that the International Team members have plenty of simulations available for all planned studies. Therefore, we are confident that we will be able to produce reference articles exploring the mutual relations between these realms of helicity applications, reformulating the employed method within the same theoretical framework, and which will be relevant to different communities in Astrophysics.

Goals and Meeting Plan of the International Team

The above scientific program will be covered during three meetings of 4-5 days each, within a 18-20 months period. The programmatic backbone of these meetings is the following:

First meeting, envisioned for October-December 2018

1. Presentations and comparison of existing methods for the computation of helicity
2. Review of numerical simulations to be used as test cases
3. Review of SDO observations for the build of observational test cases

Second meeting, to be held about 9 months after the first one.

1. Discussion of the results from the application of methods to the numerical and observational test cases decided during the first meeting
2. Review of the theoretical implication and needs for generalizations or reformulations of existing methods
3. Assessment of the need for specific handling of data and observations prior to the computations of helicity estimations
4. Layout of new numerical simulations specifically designed to address possibly remaining open questions

Third meeting, to be held about 18 months after the first one.

1. Results of application to observations using available and newly obtained simulations
2. Observational challenges, as opposed to applications to test cases
3. Assessment of magnetic helicity applicability in different fields

We expect to be able to produce at least two review papers, one covering the topic of spectral and integral methods of helicity estimation, the second one surveying the application to simulations and observations. Additional papers more focused on specific aspects of the comparison will be encouraged.

International Team Composition

Table 1: Confirmed members of the proposed International Team

Name	Area of expertise	Country
Gherardo Valori (Team Leader)	Helicity in finite volume, Force-free modeling	UK
Etienne Pariat (team co-leader)	Helicity flux, MHD modeling	France
Axel Brandenburg	Spectral methods for helicity estimations	Sweden/USA
Simon Candelaresi	Gauges for helicity in numerical simulation	UK
Yang Liu	Helicity flux, Observations	USA
Kostas Moraitis	Helicity in finite spherical volumes	France
Julia Thalmann	Helicity in finite volumes, Force-free modeling	Austria
Anthony Yeates	Field-line helicity, helicity in global simulations	UK

We propose to assemble an ISSI International Team of eight researchers (cf. Table 1) to investigate, develop, and evaluate the most recent spectral and finite-volume methods for the estimation of magnetic helicity, in both Cartesian and spherical geometries, using both numerical simulation and applications to solar observations. The team members are selected so as to provide the optimal combination of expertise required for the realization of the proposed project. Specific expertise in the preparation of observational data from the *Solar Dynamics Observatory* is also provided by group members. Therefore, the team will be able to function in complete autonomy for the completion of the project.

The international level of the Team is guaranteed by representatives of five countries, including four ESA Member States. The specific combination of expertises required by the proposal did not favour a better gender balance. We intend to improve on that aspect with the choice of the Young Scientists.

Added value of ISSI

We are now at the crucial time at which the available physical concept of magnetic helicity must be tested for practical applicability to real observations. Efforts in developing tools based on magnetic helicity have been made in several fields of space science that normally do not communicate with each other. Therefore, in order to progress in the use of magnetic helicity at large, it is urgent to bring together such developments under the same theoretical framework, to check their mutual consistency, and to benchmark them in numerical tests and in real applications. Such challenging steps are appropriate for a small group of representative experts from different fields that can explore all its implications. But, given the wide breadth of specializations involved, such a group is extremely difficult to gather. ISSI provides the unique environment that supports the collaboration among scientists of such specialized and strongly focused research disciplines, in order to form a motivated team of experts addressing such pressing, well-defined questions.

Additionally, the financial support provided by ISSI aids the progress on such a topic by offsetting the cost of assembling team members in a common location, who (for the team proposed here) would otherwise be dispersed across several countries. The application to ISSI-Bern is motivated by its most appropriate location given the countries of residence of the team members (see Table 1).

The International Team we propose here builds on the very successful experience of a previous ISSI team[1] on magnetic helicity, but with a somewhat different composition, reflecting the new innovative set of topics, and broadening the spectrum of analyzed models with a definite cross-disciplinary intent. The mixture of theory and modeling, benchmarking methods on both test cases and applications to real data observations, that characterized that team resulted in *seven refereed publications* with ISSI acknowledgement, which would have not been possible without the logistic and financial support of ISSI. The current International Team proposal is informed by the same spirit, and we expect it to be equally successful.

Required support

We intend to profit from the Young Scientist scheme, with beneficiaries to be identified upon approval of this proposal.The proposed ten-members International Team will meet over three meetings lasting 4-5 days each, over a 18-20 months period. For the meetings, the International Team will require a meeting room for about 10–12 people, with projection equipment and internet connection. We request the standard financial support of the team members’ local expenses. Publication charges and computing facilities will be covered by the home institutions of the team members.

Annex 1 : References

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